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CONCEPTUAL DESIGN OF AN IN-SPACE CRYOGENIC FLUID MANAGEMENT FACILITY

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16. Abstract

This study presents the conceptual design of a Spacelab experiment to develop the technology associated with low-gravity propellant management. The proposed facility consists of a supply tank, receiver tank, pressurization system, instrumentation and supporting hardware. A phased approach was assumed for the facility with Phase I concentrating on technology issues related to the supply tank and Phase II concentrating on technology issues related to the receiver tank.

The study consisted of three major tasks: Preliminary Facility Definition, Facility Conceptual Design and Facility Development Plan. The Preliminary Facility Definition identified the experimental objectives, the receiver tank to be modeled and constraints imposed on the design by the Space Shuttle, Spacelab and scaling requirements. The Conceptual Design includes the general configurations, flow schematics, insulation systems, instrumentation requirements and internal tank configurations for both phases. Analysis of the conceptual design included thermal, structural, fluid and safety/reliability aspects of the CFMF. Facility Development Plan includes schedule and cost estimates for the facility. A program Work Breakdown Structure and Master Program Schedule were prepared for a 7-year program costing $7.5M (in December 1980 dollars), excluding Shuttle user costs.

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FOREWORD

This Final Report summarizes the technical effort conducted by Beech Aircraft Corporation under Contract No. NAS 3-22260. The National Aeronautics and Space Administration, Lewis Research Center, administered the contract.

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In addition, Mr. M. H. Blatt of Science Applications, Inc., provided the receiver tank modeling analyses, including the discussions of the transfer processes and scaling analysis. Mr. Blatt provided design information for the helium diffuser, start basket and tapered vent tube.

All data is presented in the International Systems of Units as primary units with English units as the secondary system.

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SUMMARY

This study presents the conceptual design of a Spacelab experiment to develop the technology associated with low-gravity propellant management. The proposed facility consists of a supply tank, a receiver tank, pressurization system, instrumentation and supporting hardware.

The study consisted of three major tasks: Preliminary Facility Definition, Facility Conceptual Design and Facility Development Plan.

The Preliminary Facility Definition required the determination of experimental objectives, the receiver tank to be modeled, constraints imposed on the design by the Space Shuttle and Spacelab and applicable transfer processes and scaling analyses. As a result of the preliminary definition, a Personnel Orbital Transfer Vehicle (POTV) liquid hydrogen tank was selected as the tank to be modeled. The supply tank is the Cryogenic Fluid Management Experiment (CFME) liquid hydrogen tank. A phased approach was assumed for the facility with Phase I concentrating on technology issues related to the supply tank and Phase II concentrating on technology issues related to the receiver tank. From the size constraints imposed on the facility design by a Spacelab pallet and from the amount of liquid available from the CFME tank, it was determined that a 0.36 and 0.165 scaled POTV receiver tank would be used for Phase I and Phase II, respectively.

The Preliminary Facility Definition was used in preparation of the Conceptual Design which included general configurations, flow schematics, insulation systems, instrumentation requirements and internal tank configurations for both phases. Analysis of the conceptual design included thermal, structural, fluid and safety/reliability aspects of the CFMF.

The conceptual design was used to prepare a Facility Development Plan. The proposed development plan includes schedule and cost estimates for the facility. A program Work Breakdown Structure and Master Program Schedule were prepared for a 7-year program costing $7.5M (in December 1980 dollars), excluding Shuttle user costs.

1.0 INTRODUCTION

This report presents the work performed under NASA Contract NAS 3-22260 entitled, "Conceptual Design of an In-Space Cryogenic Fluid Management Facility." The purpose of this study is the development of a conceptual design for a Spacelab low-g facility which would demonstrate the technology required for cryogenic propellant management. The facility consists of a supply tank, receiver tank, pressurization system, instrumentation and supporting hardware (i.e., lines, valves and support structures) mounted on a single Spacelab pallet. Figure 1-1 shows the CFMF mounted in the Space Shuttle payload bay. Three missions will be flown with different facility configurations. The supply tank will contain a liquid acquisition system; the third mission receiver tank will be equipped with a start basket. The facility is launched with the supply tank filled with liquid hydrogen (LH_2) and the receiver tank empty. In orbit, experiments will be conducted to evaluate liquid expulsion, mass gauging, liquid transfer, receiver tank cooldown and fill, and start basket performance.

The study is divided into three tasks:

1. Preparation of a preliminary facility definition.
2. Development of the conceptual design for the facility.
3. Preparation of a facility development plan.

These tasks contain the conceptual design of the In-Space CFMF, an analysis of the transfer processes, and structural and thermal analyses of the receiver tank. Instrumentation requirements, with regard to type and location, are included in this report. Ground support equipment, required to load the In-Space CFMF, is also discussed. General layout drawings and flow schematics were prepared for each phase of the facility. In addition, this report contains cost and schedule estimates for the development of the In-Space CFMF.

1.1 Scope. The scope of this study was to provide a conceptual design and development plan for a Spacelab facility which would demonstrate low-g transfer of cryogenic liquids. Based upon the conceptual design presented in this report, budgetary and planning (B&P) estimates for the facility were made. The design of the facility was to be suitable for a minimum of three missions with experimental objectives identified for each mission. The utilization of published low-gravity transfer analyses and techniques were emphasized.

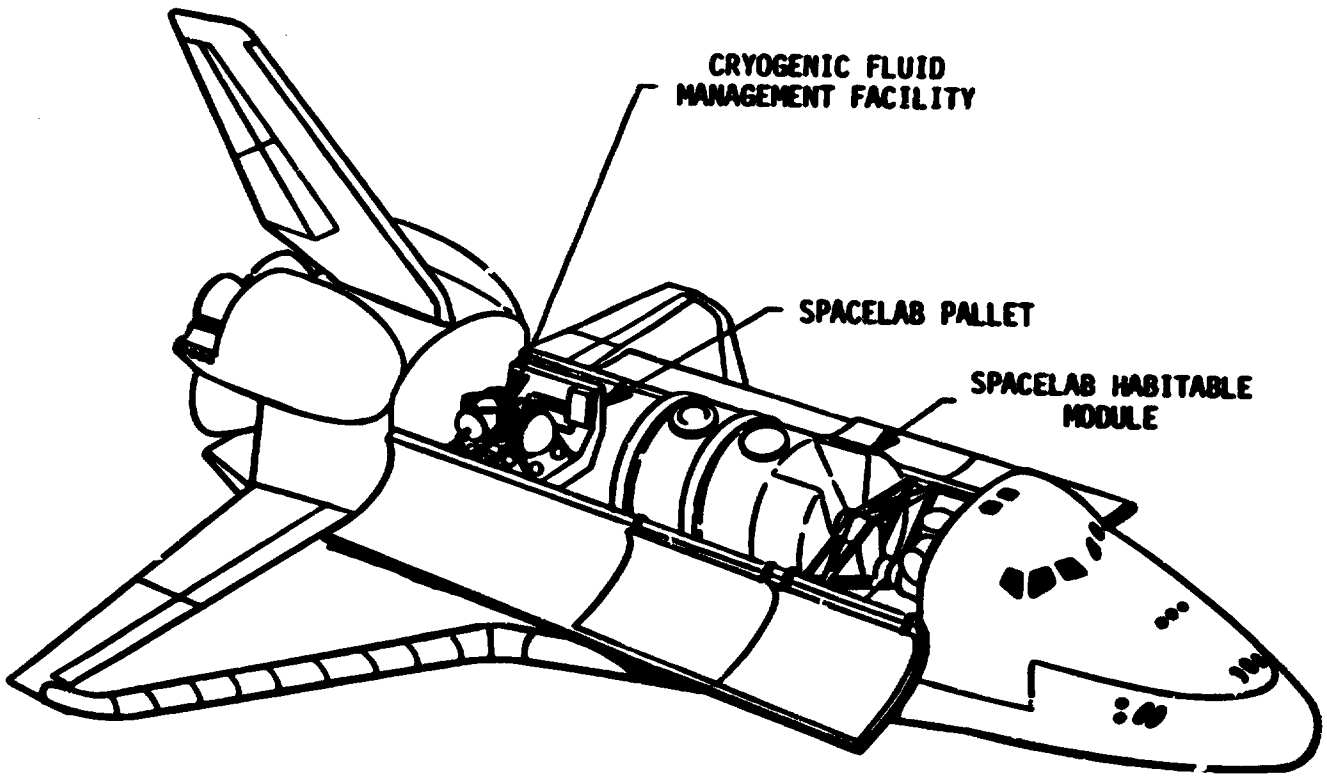

Figure 1-1 CRYOGENIC FLUID MANAGEMENT FACILITY

1.2 Ground Rules. The supply tank to be used in the CFMF is the LH_2 tank developed for the Cryogenic Fluid Management Experiment (CFME) Program. This tank is currently undergoing final design, and therefore, was not analyzed as part of this study. In addition, the design of the CFMF was to utilize as much hardware from the CFME Program as possible. CFME helium pressurization bottles and supply tank support system were to be used. The CFME Data Acquisition and Control System and data recorder were examined to determine their suitability for the entire facility.

The receiver tank selected for modeling was a Personnel Orbital Transfer Vehicle (POTV) liquid hydrogen tank. Selection of this tank resulted from a review of low-g liquid transfer literature which identified the POTV as the most likely near-term application of liquid cryogen transfer technology.

2.0 PRELIMINARY FACILITY DEFINITION

The preliminary facility definition was based upon demonstrating the technology required for low-g cryogenic propellant management. The experimental objectives of the facility were defined and a literature review was conducted to determine the receiver tank to be modeled. The geometric, thermal and structural constraints imposed on the facility by the Space Shuttle, the Spacelab pallet and the Cryogenic Facility Management Experiment (CFME) supply tank determined the extent to which the receiver tank could be modeled. Potential receiver tank models were selected based on these facility design constraints. Determination as to whether the data obtained from the experiment could be scaled to the full-scale Personnel Orbital Transfer Vehicle (POTV) tank required a scaling analysis of the transfer processes.

2.1 Experimental Approach and Objectives. The following paragraphs describe the approach taken for the preliminary facility definition; primary and secondary objectives of the facility are identified.

2.1.1 Phased Approach. A two-phase approach was utilized in the preliminary facility definition. This was to maximize the technical benefit to be gained and to provide a more cost effective hardware development program. The phased approach is the separation of the technologies associated with propellant transfer: (1) supply tank storage, liquid acquisition and transfer line chilldown; (2) receiver tank chilldown, fill and liquid acquisition.

2.1.1.1 Phase I. Phase I will consist of a single mission and will focus on the technologies associated with the supply tank liquid expulsion and transfer line and receiver tank cooldown. The performance characteristics of the supply tank will be determined. In particular, performance of the capillary device and Thermodynamic Vent System (TVS) will be assessed. The facility hardware for this phase will consist of the supply tank, the transfer line, a bare receiver tank and instrumentation required to provide tank quantity and quality/density flow measurements.

2.1.1.2 Phase II. Phase II will consist of two missions and will deal primarily with the receiver tank technology associated with cooldown and fill. The first mission will utilize a bare receiver tank and will demonstrate a receiver tank no-vent fill following cooldown. The second mission will utilize a fully configured receiver tank (with a start basket). This mission will demonstrate the initial filling, liquid expulsion and refill capabilities of the start basket.

2.1.2 Experimental Objectives. The experimental objectives for each phase of the facility were determined to maximize the data obtained and provide an attractive technical benefit-to-cost ratio.

Experimental Objectives, Phase I. Table 2-I is the primary and secondary objectives for Phase I. Several of the secondary objectives are concerned with the helium pressurization system and its impact on the supply tank (e.g., the effect of ambient helium on the capillary device retention capability and supply tank thermodynamics). Demonstration of low-g quality/density measurement is a critical objective of Phase I in that this instrumentation is required for the following two missions. Capillary device behavior during transient outflow is significant due to the need for pulsed outflow during receiver tank cooldown.

TABLE 2-I PHASE I FACILITY OBJECTIVES

Mission	Hardware	Primary	Secondary
1	Supply Tank, Transfer Line and Bare Receiver Tank	o Evaluate Performance of Supply Tank Channel Screen Liquid Acquisition Device for Cryogenic Liquid o Demonstrate On-Orbit Operation of Supply Tank Quantity Gauging System o Collect Transfer Line Chilldown Data o Evaluate Effectiveness of Receiver Tank Chilldown	o Demonstrate supply tank TVS. o Evaluate helium pressurization systems. o Demonstrate low-g liquid/vapor quality and mass flow measurement. o Examine effect of ambient helium pressurization on the supply tank screen retention capability. o Determine impact of ambient helium pressurization on the supply tank thermodynamics. o Verify analytical model of receiver tank chilldown. o Determine capillary device pressure characteristics for transient flow.

Experimental Objectives, Phase II. The primary and secondary objectives for each mission of Phase II are given in Table 2-II. The primary objectives are demonstration of receiver tank filling, operation of an internal TVS and start basket fill/refill capabilities. These

objectives were determined based on the assumption that all Phase I objectives were satisfactorily met. Mission Two will demonstrate the cooldown and no-vent fill of the bare receiver tank. The primary objectives of Mission Three are the demonstration of a no-vent liquid fill of a fully configured receiver tank, and filling, liquid expulsion and refilling of a start basket.

TABLE 2-II PHASE II FACILITY OBJECTIVES

Mission	Hardware	Primary	Secondary
2	Supply Tank, Transfer Line and Bare Receiver Tank	o Demonstrate No-Vent Liquid Fill o Demonstrate Receiver Tank Refill o Evaluate Receiver Tank Internal TVS	o Obtain data for receiver tank during prechill, chill and fill. o Verify scaling analysis. o Demonstrate helium vent using vent device and/or propellant settling.
3	Supply Tank, Transfer Line and Fully Configured Receiver Tank	o Demonstrate No-Vent Liquid Fill of Fully Configured Receiver Tank o Demonstrate Start Basket Fill and Refill	o Evaluate start basket performance during coast. o Investigate techniques for reducing vapor bubble collapse times. o Obtain data for receiver tank during prechill, chill and fill. o Evaluate impact of additional wetted tank mass on prechill. o Test TVSs for receiver tank.

2.2 Receiver Tank to be Modeled. After the objectives for both phases of the facility were determined, the tank to be modeled was selected. A literature review was conducted to determine the most likely candidate for on-orbit propellant transfer and its configuration and operating modes.

2.2.1 Literature Review. Data on typical vehicles requiring propellant transfer and propellant depots were tabulated for both cryogenic and noncryogenic fluids. This information, presented in Table 2-III, was obtained from References 1 through 8. Review

TABLE 2-III CANDIDATES FOR PROPELLANT TRANSFER EXPERIMENT MODELING

Vehicle/Depot	Reference	Fluid	Tank Configuration	Insulation	Internal Hardware	Special Procedures	Other
Orbital Transfer Vehicle	1, 2	LO_2	Ellipsoidal cylinders, two tanks, 6.9 m (22.8 ft) diameter x 3.5 m (11.4 ft) long, 1.38 bulkhead, 172 to 365 KPa (25 to 53 psia). Surface Area = 158.9 m^2 (1710 ft^2) per tank. Volume = 13.0 m^3 (460 ft^3) per tank. Tank Mass = 1151 Kg (2536 lb) per tank. Wieded aluminum.	20 layers MLI as above.	Start basket Thermodyname Vent System (TVS).	Same as for POTV.	Stage 1 $\dot{m}$ = 67.7 Kg/sec (149 lb/sec). Stage 2 $\dot{m}$ = 338 Kg/sec (745 lb/sec).
Orbital Transfer Vehicle	1, 2	Helium	Helium bottles.	-	-	Modular transfer of helium bottles.	-
Low Thrust Vehicle, Concepts One and Two	1	MMH	Spherical (RCS) titanium, 0.94 m (37 in) diameter, two tanks.	-	Acquisition device.	Liquid spray fill.	-
Low Thrust Vehicle, Concepts One and Two	1	N_2O_4	Spherical (RCS) titanium, 0.94 m (37 in) diameter, two tanks.	-	Acquisition device.	Liquid spray fill and helium venting. Drain tank to other tank and then vent. N_2H_4 is more difficult to handle.	Use of a helium recovery system is advocated for venting.
Low Thrust Vehicle, Concepts One and Two	1	MMH	Cylinder OMS, Shuttle with bulkhead, two tanks, 24.0 m (943 in) long titanium, 1.2 m (49 in) diameter. Surface Area = 3.6 m^2 (39.1 ft^2) per tank. Volume = 2.6 m^3 (90 ft^3) per tank. Mass = 2131 Kg (4693 lb) MMH per tank. Pressure = 1.8 MPa (255 psia). 253 Kg (558 lb) per tank.	-	Acquisition device galleries.	-	-
Low Thrust Vehicle, Concepts One and Two	1	N_2O_4	Cylinder OMS, Shuttle with bulkhead. Same as MMH geometry. 3527 Kg (7768 lb) N_2O_4 per tank.	-	Acquisition device galleries.	-	-

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TABLE 2-III CANDIDATES FOR PROPELLANT TRANSFER EXPERIMENT MODELING (Continued)

Vehicle/Depot	Reference	Fluid	Tank Configuration	Insulation	Internal Hardware	Special Procedures	Other
Common Stage OTV (POTV)	2	LH_2	5.9 m (234 in) cylindrical section, 4.3 m (169 in) diameter 1.38 elliptical heads (two tanks). Surface Area = 128 m^2 (1378 ft^2) per tank. Volume = 116 m^3 (4100 ft^3 per tank. Tank Mass = 448 Kg (986 lb) per tank.	Multilayer Insulation	Material - 2219-T87 Al start baskets, zero-g vent systems, mechanical separators, spray nozzle in basket and outside baskets (3 per LH_2 tank).	No blowdown of helium required prior to refilling. Prechill charge and vent required. Chilldown and filling liquid spray into basket reduces bubble collapse time.	Stage 1 $\dot{m}$ = 11.2 Kg/sec (24.7 lb/sec). Stage 2 $\dot{m}$ = 5.6 Kg/sec (12.35 lb/sec). (Consideration of start basket bubble collapse is not adequate.)
Common Stage OTV (POTV)	1 2	LO_2	1.8 m (70 in) cylindrical section, 3.8 m (150 in) diameter 1.38 elliptical bulkheads, 44,467 (97,944 lb) in each tank (two tanks). 90,037 Kg (198,320 lb) capacity. Surface Area = 58.9 m (634 ft^2) per tank. Volume = 41.3 m^3 (1457 ft^3) per tank. Tank Mass = 260 Kg (573 lb).	Multilayer Insulation	Material - 2219-T87 Al start baskets, zero-g vent systems, mechanical separators, only one spray nozzle.	Two blowdowns required with solar heating between blowdown. No prechill required. Childown and filling directly.	Stage 1 $\dot{m}$ = 67.6 Kg/sec (149 lb/sec). Stage 2 $\dot{m}$ = 33.8 Kg/sec (74.5 lb/sec). (Consideration of venting in low-g with a passive system was not addressed).
Common Stage OTV (POTV)	1, 2	N_2H_4	1.0 m (40 in) diameter (4), 431 Kg (950 lbs) in each tank.	None (heaters).	-	-	-
Common Stage OTV (POTV)	1, 2	N_2, O_2	-	-	-	-	-
Common Stage OTV (POTV)	1, 2	Helium	0.51 m (20 in) diameter (4), 20.7 MPa (3000 psia).	None (heaters).	-	Replaced bottles.	-
(COTV) Orbital Transfer Vehicle	1 2	LH_2	Ellipsoidal cylinders, two tanks, 8.1 m (26.6 ft) diameter x 11.6 m (38.1 ft) long. 1.38 bulkhead. Ellipsoidal cylinder. Surface Area = 338.9 m^2 (3648 ft^2) per tank. Volume = 548.3 m^3 (19,363 ft^3) per tank. Tank Mass = 2230 Kg (4911 lb) per tank. Welded aluminum, 172 to 200 KPa (25 to 29 psia).	20 layers of coated aluminized Superfloc MLI	Start basket thermodynamic vent system same as POTV, except tanks are completely inerted through refilling system.	Refill operations are the same as for the common stage OTV. This vehicle has capability for reclaiming residuals.	Could have helium or autogenous pressurization. Could have start baskets or no start baskets. Advanced Attitude Control System (AACS) uses O_2 and H_2. Advanced main engine has zero NPSP requirement and does not use helium. Stage 1 $\dot{m}$ = 13.5 Kg/sec (29.7 lb/sec). Stage 2 $\dot{m}$ = 5.6 Kg/sec (12.35 lb/sec).

TABLE 2-III CANDIDATES FOR PROPELLANT TRANSFER EXPERIMENT MODELING (Continued)

Vehicle/Depot	Reference	Fluid	Tank Configuration	Insulation	Internal Hardware	Special Procedures	Other
Low Thrust Vehicle, Concepts One and Two	1	Helium	1.0 m (40 in) diameter sphere (2).	-	-	Modular transfer.	-
CFME	3	LH_2	Thermal Mass = 13.6 Kg (30 lb), 345 KPa (50 psia) LH_2 vapor pressure + 69 KPa (10 psia), 690 KPa (100 psia) maximum allowable, sphere ID 1.05 m (41.17 in), 0.60 m^3 (21.186 ft^3) storage volume, 6061 Al-T62.	Boiler shield, 75 layers MLI between shield and outer shield.	TVS, liquid out of channel acquisition device circulated into the boiler shield.	-	-
PRSA	4	LH_2	Storage Volume = 0.61 m^3 (21.395 ft^3). PVID = 1.05 m (41.516 in). Maximum Pressure = 2.3 MPa (335 psi). Tankage Weight = 102 Kg (225 lb). Material = 2219 Al.	Vapor cooled shield, double silverized Kapton.	Heater, density probe (capacitance).	-	-
PRSA	4	LO_2	Volume = 0.32 m^3 (11.237 ft^3). PVID = 0.85 m (33.435 in). Maximum Pressure = 7.2 MPa (1050 psi). Outer shell 2219 Al. Pressure vessel Inconel 718.	No shield, double silverized Kapton.	Heater, density probe.	-	-
ET Propellant Depot	1	LH_2/ LO_2, GHe	LH_2 tank - spherical dewar inside ET LH_2 tank, 4.3 m (14 ft) ID, 4.6 m (15.2 ft) OD. Tank Pressure = 138 KPa (20 psi). 2219-T87 Al alloy. LO_2 tank is the ET LO_2 tank. 0.9 m (3 ft) LH_2 helium bottles in dewar, 20.7 MPa (3000 psi) titanium.	LH_2 - 45 layers MLI. LO_2 - 20 layers MLI.	TVS both tanks. Partial acquisition devices for both tanks. (Settling required.) Reliquefaction system.	-	-

TABLE 2-III CANDIDATES FOR PROPELLANT TRANSFER EXPERIMENT MODELING (Continued)

Vehicle/Depot	Reference	Fluid	Tank Configuration	Insulation	Internal Hardware	Special Procedures	Other
Orbital Propellant Depot	1	LH_2/ LO_2	Dewars shown as baseline. LH_2 hemispherically ended cylinders. 2.9 m (113.3 in) long, 4.4 m (174 in) diameter, 207 KPa (30 psi), 5189 Kg (11,429 lb). LH_2 - 2219-T87 Al alloy. Surface Area = 92 m^2 (992 ft^2). LO_2 - 4.0 m (157 in) OD spherical dewar. 207 KPa (30 psi), 43.8 m^2 (80,000 lb) LO_2. Surface Area = 43.8 m^2 (471.4 ft^2). Mixture Ratio = 6/1. 2219-T87 Al alloy.	LH_2 - 20-layer MLI blankets. LO_2 - 20-layer MLI blankets.	Channel type acquisition system.	-	Purged MLI is shown as an alternative, but not discussed relative to the dewar approach.
Orbiter Tanker Configuration (Use for POTV)	1,5,6,7	LH_2/ LO_2	Nested tanks. 2.2 m (85 in) diameter cylinder. Hemispherical ends. WP = 39,500 Kg (87,000 lb). Mixture Ratio = 6/1.	Vacuum jacketed dewar, 10 layers MLI.	Channel type capillary devices.	Overlapping transfer with LH_2 initiated first.	-
Test Tank (0.2 Scale).	1	LH_2	1.8 m (71.3 in) long. 1.2 m (46.8 in) cylinder (length). 0.8 m (33.8 in) diameter. a/b = 1.38. Surface Area = 5.1 m^2 (55 ft^2). Tank Volume = 0.93 m^3 (32.76 ft^3) Allowable Pressure = 261 KPa (37.9 psi). 2219-T87 Al alloy.	Strip heaters.	No details given.	Scale model test variables are given. Operations are not shown.	Double rack sizes.

TABLE 2-III CANDIDATES FOR PROPELLANT TRANSFER EXPERIMENT MODELING (Continued)

Vehicle/Depot	Reference	Fluid	Tank Configuration	Insulation	Internal Hardware	Special Procedures	Other
Test Tank (0.3 Scale)	1	LH_2	2.7 m (107 in) long. 1.8 m (70.26 in) cylinder (length). 1.3 m (50.7 in) diameter. a/b = 1.38. Surface Area = 12.1 m^2 (129.86 ft^2). Tank Volume = 3.1 m^3 (110.65 ft^3). Allowable Pressure = 214 KPa (31 psi). 2219-T87 Al alloy.	-	-	-	-
Test Tank (To fit double rack)	1	LH_2	1.2 m (47.0 in) long. 1.1 m (43.0 in) cylinder (length). 0.46 m (18.0 in) diameter. a/b = 1.38. Surface Area = 1.6 m^2 (17.6 ft^2). Tank Volume = 0.16 m^3 (5.7 ft^3). Allowable Pressure = 483 KPa (70 psi). 2219-T87 al alloy.	-	-	-	-
Dedicated Shuttle Experiment (3/4 scale receivers)	8	LH_2 Supply Dewar	4.2 m (164 in) diameter cylinder. Spherical bulkheads. 2.6 m (103 in) straight section. Surface Area = 89 m^2 (955 ft^2). Volume = 73.6 m^3 (2600 ft^3). Allowable Pressure = 214 KPa (31 psia).	MLI	Channel type capillary acquisition system. TVS. Looks like helium pressurization stored in ambient bottles.	Vent down to remove helium. Prechill charge and vent. Tank fill.	MLI with purge bag selected. Dewars probably would not be as costly as they showed.
Dedicated Shuttle Experiment (3/4 scale receivers)	8	LH_2 Receiver	4.7 m (185.5 in) length cylinder. 3.2 m (124.5 in) diameter. Surface Area = 60 m^2 (643 ft^2). Volume = 49 m^3 (1730 ft^3). Wall heaters (not a dewar).	MLI in gore and cap section, 40	No acquisition system. Two spray manifolds and a single nozzle.	Preheat propellant to chill down with saturated vapor.	True 1/2 scale and 1/4 scale also shown. Selected a 1/2 scale and 1/4 scale tank to both be tested as receivers. 1/2 Scale = 14.5 m^3 (511 ft^3). 1/4 Scale = 1.8 m^3 (64 ft^3).

TABLE 2-III CANDIDATES FOR PROPELLANT TRANSFER EXPERIMENT MODELING (Concluded)

Vehicle/Depot	Reference	Fluid	Tank Configuration	Insulation	Internal Hardware	Special Procedures	Other
POTV	8	LH_2	LH_2 Tank = 127 KPa (18.4 psi). 6.3 m (247.3 in) length cylinder. Elliptical heads, a/b = 1.38. 4.2 m (166.0 in) diameter. 2219-T87 Al alloy. Surface Area = 129 m^2 (1390.3 ft^2). Volume = 116 m^3 (4100 ft^3).	Multilayer Insulation	TVS. Two spray nozzles, pressurant diffuser, acquisition device shown in detail.	Prechill charge and vent to prevent venting liquid during chilldown.	Other OTV candidates are sketched, including AMOOS, minimum length OTV, Modular OTV and Centaur.
POTV	8	LO_2	LO_2 Tank. 1.8 m (70 in) straight cylinder. 3.8 m (150 in) diameter. Elliptical heads, a/b = 1.38.	Multilayer Insulation	TVS. Bubbler ring for pressurization. Spray nozzle acquisition system.	Vent down to remove helium prior to refill.	-

of these reports indicated that the POTV is a promising candidate vehicle for future space based systems in the near term.

The cryogenic fluids used on the POTV are liquid hydrogen (LH_2) and liquid oxygen (LO_2). The LH_2 tank was selected for modeling for the following reasons:

1. Receiver tank chilldown and fill is more difficult to accomplish with LH_2 than with LO_2 (reference Table 2-IV).

2. Because of its lower surface tension, low-g liquid acquisition is more difficult (Reference 9).

3. There are fewer safety problems associated with LH_2 than LO_2.

TABLE 2-IV CRYOGENIC FLUID TRANSFER OPERATIONS ASSESSMENT (POTV)

Process	LH_2 Tank	LO_2 Tank
Line Childown	Care must be taken to avoid pressure surges.	Care must be taken to avoid pressure surges. Pressure surges are aggravated by high liquid density.
Tank Childown	Prechill charge and vent recommended for chilldown to eliminate problems of venting liquid during chilldown.	Tank pressure will not exceed vent pressure during chilldown. Prechill charge and vent is therefore not required.
Tank Filling	Good mixing, using spray nozzles, jets or mixers is required to maintain thermal equilibrium and low tank pressures during fill (higher mixer power is required for LH_2 than for LO_2 to achieve a given bubble diameter according to Reference 1).	Good mixing, using spray nozzles or mixer is required to maintain thermal equilibrium and low tank pressures during fill.
Tank Refilling (With GHe Pressurant)	Removal of helium is required to prevent tank overpressure during refilling. Means of venting helium must be provided.	Removal of helium is required to prevent tank overpressure during refilling. Means of venting helium must be provided.
Vapor Removal From the Acquisition Device	Inflow of liquid in the start basket during fill should accomplish bubble collapse. Use of helium to condense vapor trapped in the acquisition device during filling is a secondary approach. Bubble collapse is more difficult than with LO_2 (e.g., approximately an order of magnitude more time is required for the same bubble size and level of subcooling).	Use helium to condense vapor trapped in the acquisition device during fill.

2.2.2 Determination of POTV Characteristics. The following paragraphs describe the POTV configuration and operations.

2.2.2.1 General Configuration. The general configuration of the POTV liquid hydrogen tank is shown in Figure 2-1. The liquid hydrogen tank is a 2219 aluminum cylindrical tank with elliptical heads, has a volume of 116.1 m^3 (4100 ft^3), weighs approximately 453 kg (998 lbs) and has a total tank surface area of 128.6 m^2 (1386 ft^2). The tank insulation system consists of 20 layers of double aluminized Superfloc. The tank contains a vapor only TVS, pressurization diffuser, propellant acquisition device and a fill manifold utilizing two spray nozzles. A summary of the POTV liquid hydrogen tank characteristics is contained in Table 2-V.

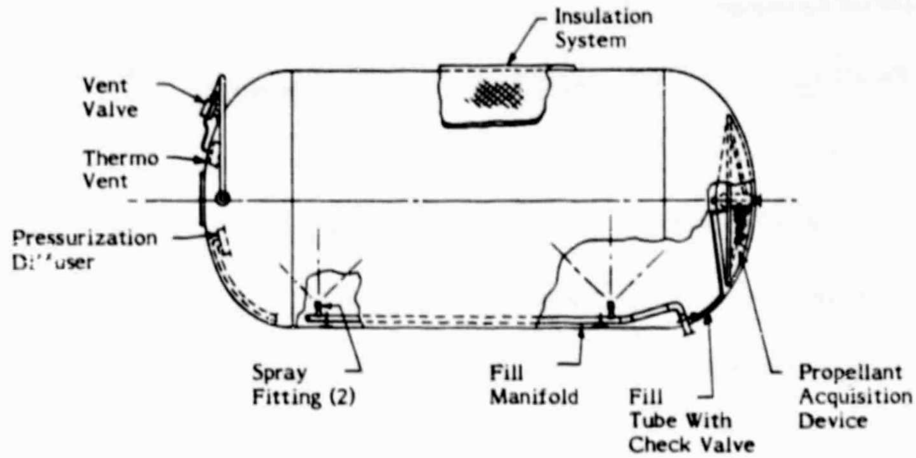


Figure 2-1 POTV HYDROGEN TANK GENERAL CONFIGURATION (Reference 8)

2.2.2.2 POTV Fill/Refill Operations. The POTV cryogenic fluid transfer operations (fill/refill) are summarized in Table 2-IV. These operations are: transfer line chilldown, receiver tank prechill, chill and fill, vapor removal within the capillary device and tank refilling. This technique for propellant transfer was developed and discussed in Reference 10. An analysis of the transfer operations was conducted and is summarized in Table 2-VI.

TABLE 2-V POTV CONDITIONS - LH_2 TANK

Item	Value		Reference
o Tank Configuration:			
Geometry	Cylindrical With 1.38 Elliptical Heads		8
Volume	116 m^3	(4100 ft^3)	8
Diameter	4.2 m	(166 in)	8
Cylindrical Length	6.2 m	(246 in)	8
Total Length	9.3 m	(366 in)	8
Surface Area	128.8 m^2	(1386 ft^2)	8
Thickness	1.27 mm	(0.05 in)	8
Material	2219 T87 Aluminum		8
o Tank Weights:			
Dry Tank (2219 T87 Al)	453 Kg	(998 lbm)	8
Acquisition System	112 Kg	(247 lbm)	8
Wetted Mass	706 Kg	(1555 lbm)	8
Insulation	203 Kg	(448 lbm)	8
Total Tank System	942 Kg	(2074 lbm)	8
Loaded Fluid (LH_2)	7582 Kg	(16,700 lbm)	1
o Thermal/Fluid Parameters:			
Initial Temperature	2[illegible]°K	(520°R)	1
Inlet Fluid (LH_2)	1[illegible]3 KPa	(15 psia saturated)	1
Prechill: Fluid Velocity	3.4 m/sec	(11 ft/sec)	8
Mass Flow Rate	0.45 Kg/sec	(1 lb/sec)	1,8
Time	15 to 20 min		8
Fill: Fluid Velocity	6.7 m/sec	(22 ft/sec)	8
Mass Flow Rate	0.91 Kg/sec	(2 lb/sec)	1,8
Time	138 min		8
Prechill Temperature	126°K	(226°R)	1
Maximum Tank Pressure	172 KPa	(25 psia)	1
Insulation System	20 Layers MLI		8
Thermodynmaic Vent System Flow Rate	4.5 to 9.1 Kg/hr	(10 to 20 lb/hr)	1
Prechill Charge Terminated at	9.1 Kg	(20 lb)	1
Prechill Vent Initiated at $T_w - T_u$	5.6°K	(10°R)	1

Transfer Line Cooldown. The first step involved in filling an orbital transfer vehicle is cooldown of the transfer line. This is initiated by flowing liquid from the supply tank through the transfer line to the receiver tank. A concern during transfer line cooldown is the possibility of pressure surges. To avoid this, Reference 8 suggests that the transfer line be precooled with vent gas passed through a small line which bypasses the main valve in the transfer line.

POTV Receiver Tank Prechill. The fluid management technique discussed in Reference 11 proposes a receiver tank prechill whenever the initial tank temperature is greater than a predetermined target temperature. Above this temperature, excess pressure during the

TABLE 2-VI POTV RECEIVER TANK CONDITIONS ANALYSIS

Process	Equation	Applicability and Limits	POTV
Prechill and Tank Fill - During a gaseous hydrogen prechill, this equation was used to determine the heat transfer coefficient between the incoming hydrogen gas and the tank walls. During tank fill, this equation was used to determine the heat transfer coefficient between the dispersed hydrogen vapor bubbles and the hydrogen liquid. In both cases, the mechanical power input term, P, was replaced by an equivalent fluid power input term, $\eta \dot{m} V^2$.	$\frac{h_c}{\rho_c C_p} = 0.13 \left[\frac{\mu_c P/VO}{\rho_c^2} \right]^{1/4} (Pr)^{-2/3}$	This equation was developed by using theoretical considerations to determine the pertinent parameters and using data from experiments on mass and heat transfer in mixing vessels to evaluate the constant and exponents. The heat transfer experimental data was for fixed bodies submerged in agitated liquids. The submerged bodies included such things as heat transfer jackets, and coils and solids cast into the base of mixing vessels. The liquids included hot and cold water, glycerol, LM oil, A-12 oil and nitrating liquor (Pr ranging from approximately 2 to 10^3). The equation correlates experimental data over a range from 10^{-6} to 10^2 cm/sec for the product of variables *, although considerable scatter exists in the data. $* \left[\frac{(P_i/VO)\mu}{\rho 2} \right]^{1/4} (Pr)^{-2/3}$	Prechill: $\left[\frac{\frac{\eta \dot{m} V^2}{VO} \mu_c}{\rho_c^2} \right]$ Chill: $\left[\frac{\frac{\eta \dot{m} V^2}{VO} \mu_c}{\rho_c^2} \right]$
Tank Chill - This equation was used to determine the maximum heat transfer rate between the liquid hydrogen spray and the tank walls.	$\frac{Q_{max}}{\rho_l d^3 \lambda} = 8.44 \times 10^{-4} \left[\frac{\rho_l^2 V^2 d}{\rho_{vf} \sigma g_c} \right]^{0.341}$ where: $\lambda = h_{fg} + C_{pv} \left(\frac{T_p - T_s}{2} \right)$	This equation was developed from an experimental investigation of individual droplets of water, ethanol and acetone splattering on an inclined heated copper plate. The experimental data indicated that the maximum heat transfer per drop occurs at a saturation temperature excess of approximately 422°K (300°F). At saturation temperature excesses less than or greater than 422°K (300°F), the heat transfer per drop is significantly less than the maximum valve given by the equation. The magnitude of the maximum heat transfer per drop is given within 10 percent of the experimental results by the equation for values of the independent variable * in the range 10^3 to 10^7 (extrapolation to lower values seems reasonable) and for an impact angle of 27° (impact angle is defined as the acute angle between the drop velocity vector and the normal to the test surface). The experimental conditions of drop diameter and drop velocity ranged from 2.54 to 3.84 mm (0.100 to 0.151 in) and 1.05 to 5.9 m/sec (3.44 to 19.50 ft/sec), respectively. The experimental data showed that peak heat transfer per drop decreased with increasing impact angle and that for intermediate angles (~25° to ~60°), this affect could be accounted for by using the normal (normal to the heated surface) component of the drop velocity vector. The above equation is based on experimental data for a single collision of the drop and heated plate; therefore, it should be noted that subsequent collisions of splattered particles with the hot surface tend to increase the overall heat transfer. $* \left(\frac{\rho_l^2 V^2 d}{\rho_{vf} \sigma g_c} \right)$	Drop diameter … to 0.711 mm (… Velocities ran… m/sec (11 to 2… $\left(\frac{\rho_l^2 V^2 d}{\rho_{vf} \sigma g_c} \right)$
Prechill and Tank Chill - This equation can be used to determine the heat transfer coefficient between the incoming droplets of the hydrogen spray and the hydrogen vapor in the tank.	$Nu_f = \frac{2 + 0.6\, Re_m^{1/2}\, Pr_f^{1/3}}{(1 + B)}$ where: $B = \frac{h_s - h_d}{h_{fg}}$	This equation is based on experimental data of the heat transfer from simulated water and methanol droplets to a flow of heated air. The liquid droplets were simulated by using a sintered bronze porous sphere of diameter, 6.35 mm (0.250 in), and maintaining the sphere wetted by using a syringe pump. The flow of heated air was attained by using a wind tunnel equipped with a heater. Free stream air temperatures ranged from 200°C to 1,000°C (392°F to 1,832°F). Values of the mass transfer number, B, ranged from 0.028 to 0.43 and Reynolds Numbers ranged from 200 to 1,800.	Pr_f ranges fro… ranges from 1… from 0.05 to …
Vapor Removal From Screen Device - This equation was used to estimate the time required to condense hydrogen vapor bubbles trapped in the screen device after liquid filling. The bubbles are condensed by increasing tank pressure. **FOLDOUT FRAME**	$Y = 1 - \sqrt{\tau_H}$ where: $Y = R/R_o$ $\tau_H = (4/\pi)\, Ja^2\, (\alpha\, t/R_o^2)$	This equation is the result of a theoretical consideration of the collapse of bubbles and involves several idealizations: the inertial terms in the equation of motion for the bubble wall have been neglected and thus the collapse of the bubble is controlled by heat transfer; surface tension and viscosity affects have been neglected; the density of the vapor inside the bubble is much less than the liquid density; the vapor velocity at the bubble wall is neglected; the increase in system pressure is idealized as a step function and the bubble wall is assumed to be a plane. When this equation was compared to measurements of water vapor bubbles collapsing in liquid water, the resulting curve represented an approximate lower limit of the time required for bubbles to collapse. The measurements were for initial water vapor bubble radii ranging from 0.290 to 5.440 cm, system pressure changes ranging from 12.3 to 28.7 cm-Hg, Jakob Numbers ranging from 15.1 to 39.3 and B_{eff} ranging from 0.0026 to 0.39. B_{eff} is a parameter that is used to indicate when the bubble collapse process is controlled by heat transfer or inertia effects. When $B_{eff} < 0.05$, heat transfer controls, and when $B_{eff} > 10$, inertia controls. Bubble collapse times were in the range of fractions of a second. $B_{eff} = \psi^2 \left(\frac{\rho_C (T_{sat} - T_\infty)}{\bar{\rho}_v h_{fg}} \right)^2 \frac{a}{R_o} \left(\frac{\rho}{(P_\infty^* - P_{v,o})} \right)^{1/2}$ $\psi = \frac{2}{(T_{sat} - T_\infty)(P_\infty^* - P_{v,o})} \int_{T_\infty}^{T_{sat}} [P_\infty^* - P_v]\, dT$ $\bar{\rho}_v = \frac{1}{\Delta T} \int_{T_\infty}^{T_{sat}} \rho_v\, dT$	System press… (3.0 psi). Ja … 0.8. B_{eff} ran… 2.8×10^{-5}. For the plane … by these equat… $\Delta P = 34.3$ KP… m (13 in) and …
Vapor Removal From Screen Device - This equation can be used to estimate the maximum time required to condense hydrogen vapor bubbles trapped in the screen device after liquid filling.	$\tau_H = 1/3\, (\frac{2}{Y} + Y^2 - 3)$	This equation was developed using the same idealizations as for the equation *, except the bubble wall is assumed to be spherical with radial motion. One additional idealization introduced was that significant temperature variations occur only in a thin layer adjacent to the bubble wall. When this equation was compared to the measurements of water vapor bubbles collapsing in liquid water described for the equation *, the resulting curve represented an upper limit of the time required for bubbles to collapse. $* Y = 1 - \sqrt{\tau_H}$	For the spheri… sented by the… hrs. For P = 34.5 … 0.33 m (13 in) …
Vapor Removal From Screen Device - This equation can be used to estimate times required to eliminate vapor from the screen device when a liquid is sprayed into the screen device. The liquid spray decreases the time required to eliminate vapor from the screen device.	$t^* = \frac{1}{\dot{m}_i (h_i - h_g)} \left[VO_B\, \rho_l (u_l - h_g) + m_l \left[X\, u_v + (1 - X)\, u_l - h_g \right] \right]$	This equation was developed from an energy and mass balance analysis of the screen device and involves the following assumptions: 1. Liquid (no vapor) enters the screen device at a constant temperature. 2. Only liquid will exit the start basket; vapor is removed only by condensation. 3. Liquid inside the screen device will rapidly saturate at tank pressure due to absorbing the heat of condensation. Thus, the internal energy of the liquid inside the screen device remains constant at the saturated value corresponding to the tank pressure. 4. All liquid leaving the basket will exit saturated at tank pressure. 5. The vapor bubble pressure always equals the tank pressure. Thus, the internal energy of the vapor inside the screen device remains constant at the saturated value corresponding to the tank pressure.	For a bubble r… (13 in), cal… as a function o… level of subcoo… collapse time … than 3 minutes … (5 psia) subcoo… rate of 0.30 K…

K CONDITIONS ANALYSIS

	POTV Range	Nomenclature	Reference
the pertinent parameters and using data from constant and exponents. The heat transfer submerged bodies included such things as heat liquids included hot and cold water, glycerol,). The equation correlates experimental data considerable scatter exists in the data.	Prechill: $\left[\frac{\frac{\eta \dot{m} V^2}{VO}\mu_c}{\rho_c^2}\right]^{1/4} Pr^{-2/3}$ Ranges from 3.5 to 15 cm/sec. Chill: $\left[\frac{\frac{\eta \dot{m} V^2}{VO}\mu_c}{\rho_c^2}\right]^{1/4} Pr^{-2/3}$ Ranges from 0.28 to 3.9 cm/sec.	h_c = Convective heat transfer coefficient ρ_c = Density of continuous phase C_p = Specific heat at constant pressure μ_c = Dynamic viscosity of continuous phase P = Power input to mixer V = Fluid velocity at mixer exit VO = Volume of mixing vessel Pr = Prandtl Number ($C_p \mu_c/K$) K = Thermal conductivity $\dot{m}$ = Mass flow rate η = Efficiency	12
dual droplets of water, ethanol and acetone ated that the maximum heat transfer per drop At saturation temperature excesses less than or than the maximum valve given by the equation. ent of the experimental results by the equation to lower values seems reasonable) and for an drop velocity vector and the normal to the test ged from 2.54 to 3.84 mm (0.100 to 0.151 in) data showed that peak heat transfer per drop ° to - 60°), this affect could be accounted for locity vector. The above equation is based on e, it should be noted that subsequent collisions transfer.	Drop diameters range from 0.305 to 0.711 mm (0.012 to 0.028 in). Velocities range from 3.4 to 6.7 m/sec (11 to 22 ft/sec). $\left(\frac{\rho_l^2 V^2 d}{\rho_{vf}\, \sigma\, g_c}\right)$ Ranges from 6.72×10^3 to 7.22×10^5.	Q_{max} = Maximum heat transfer per drop ρ_L = Liquid density d = Drop diameter λ = Modified heat of vaporization h_{fg} = Latent heat of vaporization C_{pv} = Vapor specific heat at constant pressure $T_p - T_s$ = Saturation temperature excess V = Drop velocity ρ_{vf} = Density of vapor evaluated at the film temperature σ = Surface tension g_c = Newton constant	3
ated water and methanol droplets to a flow of sphere of diameter, 6.35 mm (0.25 in), and ir was attained by using a wind tunnel equipped (392°F to 1,832°F). Values of the mass transfer to 1,800.	Pr_f ranges from 0.7 to 0.8. Re_m ranges from 14 to 4,900. B ranges from 0.05 to 8.3	Nu_f = Nusselt Number with properties evaluated at the film temperature ($h_c d/K_f$) h = Convective heat transfer coefficient d = Drop diameter K_f = Thermal conductivity evaluated at the film temperature Re_m = Modified Reynolds Number ($\rho_s Vd/\mu_f$) ρ_s = Free stream density V = Velocity μ_f = Dynamic viscosity evaluated at the film temperature Pr_f = Prandtl No. with properties evaluated at the film temperature ($C_p \mu_f/K_f$) B = Mass transfer number $(h_s - h_d)/h_{fg}$ h_s = Specific enthalpy of free stream gas h_d = Specific enthalpy of vapor at droplet surface temperature h_{fg} = Latent heat of vaporization at droplet surface temperature	14
bubbles and involves several idealizations: the glected and thus the collapse of the bubble is neglected; the density of the vapor inside the ble wall is neglected; the increase in system a plane. When this equation was compared to curve represented an approximate lower limit ial water vapor bubble radii ranging from 0.290 Numbers ranging from 15.1 to 39.3 and B_{eff} hen the bubble collapse process is controlled by and when $B_{eff} > 10$, inertia controls. Bubble	System pressure changes by 20.7 KPa (3.0 psi). Ja Number is approximately 0.8. B_{eff} ranges from 1.1×10^{-3} to 2.8×10^{-3}. For the plane solution represented by these equations, t = 493 hrs for Δ P = 34.5 KPa (5 psia), R_o = 0.33 m (13 in) and R/R_o = 0.05.	α = Dimensionless bubble radius (R/R_o) R = Bubble radius R_o = Initial value of bubble radius T_H = Dimensionless time pertinent to heat transfer controlled bubble collapse $(4/\pi)\, Ja^2\, (a\, t/R_o^2)$ t = Time a = Thermal diffusivity of liquid ($K/\rho C$) K = Thermal conductivity of liquid ρ = Density of liquid C = Specific heat of liquid Ja = Jakob Number $\rho C (T_{sat} - T_\infty)/\rho_{v_{ref}} h_{fg}$ T_{sat} = Saturation temperature at final system pressure, P_∞* T_∞ = Saturation temperature at initial system pressure, $P_{v,o}$ $\rho_{v_{ref}}$ = A characteristic reference value of the equilibrium vapor density h_{fg} = Latent heat of vaporization B_{eff} = Dimensionless parameter used to determine if bubble collapse is controlled by heat transfer, liquid inertia or a combination of these two items γ = Temperature difference correction factor $\bar{\rho}_v$ = Integrated average vapor density P_∞* = Final system pressure $P_{v,o}$ = Initial equilibrium vapor pressure P_v = Equilibrium vapor pressure ρ_v = Equilibrium vapor density	17
on *, except the bubble wall is assumed to be significant temperature variations occur only ed to the measurements of water vapor bubbles represented an upper limit of the time required	For the spherical solution represented by those equations, t = 6076 hrs. For P = 34.5 KPa (5 psia), R_o = 0.33 m (13 in) and R/R_o = 0.05.	Same as above equation	17
of the screen device and involves the following ons. absorbing the heat of condensation. Thus, at the saturated value corresponding to the internal energy of the vapor inside the screen pressure.	For a bubble radius of 0.33 m (13 in), calculations performed as a function of inflow rate and level of subcooling show that collapse time should be less than 3 minutes for 34.5 KPa (5 psia) subcooling at a flow rate of 0.30 Kg/sec (2/3 lb/sec).	t* = Time required to eliminate vapor in screen device $\dot{m}_{in}$ = Mass flow rate of liquid spray h_i = Enthalpy of incoming liquid spray h_o = Enthalpy of liquid exiting screen device VO_B = Volume of screen device ρ_L = Density of liquid u_L = Specific internal energy of liquid in screen device m_i = Initial value of liquid and vapor mass in screen device x = Initial value of quality (based on mass) in screen device u_v = Specific internal energy of vapor in screen device	1

FOLDOUT FRAME

chill and fill operation will result. The prechill target temperature is defined as that temperature at which the chill and fill process can be completed without requiring further venting or exceeding the receiver tank maximum operating pressure. The prechill operation outlined in Reference 11 involves a charge, hold and vent cycle which is repeated until the POTV tank wall temperatures reaches the target temperature. This procedure minimizes the amount of liquid required for tank cooldown by maximizing the enthalpy of the fluid vented. The prechill charge is accomplished by initially injecting vapor (during transfer line cooldown) and then liquid into the POTV tank. The tank is charged until a predetermined tank pressure has been reached. Having reached that pressure, the tank enters a hold period where the tank wall transfers energy to the fluid in the tank. The hold period lasts until one of two conditions is met: either the POTV tank maximum operating pressure is reached, or the average fluid and tank wall temperatures are within approximately 5 percent of each other. Then the POTV tank will be vented to a sufficiently low pressure for the next prechill cycle.

POTV Tank Chill. Following prechill, the receiver tank vent will be closed and liquid flow to the receiver tank will be initiated. Film boiling will occur at the wall as liquid strikes the warm surface and the resulting evaporation will increase the tank pressure. The prechill target temperature was selected to assure that this pressure rise does not exceed the maximum POTV tank operating pressure. The chill process continues until the wall temperature reaches saturated liquid temperature. At this point, the fill process begins.

POTV Tank Fill. The POTV tank fill is a continuation of the liquid inflow initiated for the tank chill, beginning when the tank temperature reaches the saturation liquid temperature.

POTV Vapor Removal from Capillary Device. The final phase of the POTV fill is the collapse of vapor in the capillary device. Two methods of vapor bubble collapse, active and passive (Reference 11), are described in the following paragraphs.

The passive method uses conductive heat transfer to cool and condense the vapor. Using helium pressurization to subcool the liquid, the bubble collapse times for the POTV are on the order of three to four hours for the largest spherical bubble trapped within the screen device. (Up to 33 cm (13 in) radius can theoretically be trapped between the channels in the start basket). These times may be unacceptable; however, this technique does offer the simplest approach to bubble collapse.

The active method utilizes forced convection heat transfer to condense the entrapped vapor. This method of bubble collapse requires that subcooled liquid enter the start basket during tank fill. The fluid movement, produced by the entering propellant, promotes a convective heat transfer which speeds bubble condensation. In addition, the turbulent conditions in the start basket break apart large bubbles, which will greatly reduce the collapse times. The use of active bubble collapse does not preclude the use of helium pressurization to subcool the liquid in order to complete the bubble collapse process. That is, liquid injection into the start basket reduces vapor bubble size during fill. Upon completion of fill, helium pressurization may be used to subcool the liquid to insure complete bubble collapse. This approach would require considerably less time than passive collapse.

POTV Tank Refill. Both the POTV LH_2 and LO_2 tanks require venting prior to propellant transfer to prevent overpressurization. The refill procedure utilized for a partially full tank containing helium pressurant requires venting to a helium partial pressure low enough to allow the receiver tank to be filled without further venting. Prechill and chill are not required during refill since the receiver tank is already at saturated liquid temperature.

2.3 Facility Constraints. The facility constraints are a major factor in the design of the CFMF and determine the extent to which the POTV LH_2 tank can be modeled. The external constraints on the facility are: (1) Spacelab/Shuttle constraints, (2) CFME supply tank constraints. The following paragraphs describe these constraints and their impact on the facility definition.

2.3.1 Shuttle/Spacelab Imposed Constraints. The design constraints imposed on the facility by the Space Shuttle and Spacelab pallet consisted of:

- Reactant Control System (RCS) limitations
- Coast acceleration
- Shuttle/Spacelab payload requirements

The RCS primary thrusters will be used throughout Phase II of the experiment for propellant settling. Table 2-VII gives a typical RCS propellant utilization breakdown for a 14,500 Kg (32,000 lb) payload and indicates that approximately 1811 Kg (3993 lb) of RCS propellant is available for payload support. In addition, 907 Kg (2000 lb) of RCS propellant may be obtained from the integral Orbital Maneuvering System (OMS) tanks

(Reference 19). This provision is not currently available; therefore, an attempt was made to limit the RCS propellant requirements to 1811 Kg (3993 lb). A preliminary estimate of the RCS propellant requirements is given in Paragraph 3.4.3.

TABLE 2-VII TYPICAL RCS PROPELLANT BUDGET

	Kg	lb
Total RCS Loadable	3,353	7,391
Unavailable (Includes Residuals Plus Tank Loading Tolerance)	(366)	(806)
Required for Insertion	(103)	(228)
Required for Orbital Adjustment	(408)	(899)
Required for Entry	(528)	(1,164)
On-Orbit Dispersions and Contingencies	(136)	(301)
Available for Payload Support	1,811	3,993

In addition to the RCS propellant requirements, the acceleration level generated by the RCS engines is of particular importance during Phase II because of its effect on the design and operation of the start basket. Table 2-VIII (Reference 18) gives the acceleration levels for the primary and vernier RCS thrusters into the Space Shuttle coordinate system shown in Figure 2-2. As indicated in Table 2-VIII, the maximum primary RCS thruster generates an acceleration of 0.04 g. Typical RCS propellant usage (Reference 18) is given in Table 2-IX. Based on the maximum acceleration in the -Y direction and Table 2-IX, a RCS propellant consumption rate of 14.61 Kg/sec (32.14 lb/sec) was calculated.

TABLE 2-VIII TYPICAL RCS MAXIMUM ACCELERATION LEVELS
(Reference 18)

Direction	Translational Acceleration, mps^2 (ft/sec^2)				
RCS System	+X	-X	±Y	+Z	-Z
Primary Thruster	0.18 (0.6)	0.16 (0.5)	0.22 (0.7)	0.40 (1.3)	0.34 (1.1)
Vernier Thruster	0 (0)	0 (0)	0.0021 (0.007)	0 (0)	0.0024 (0.008)

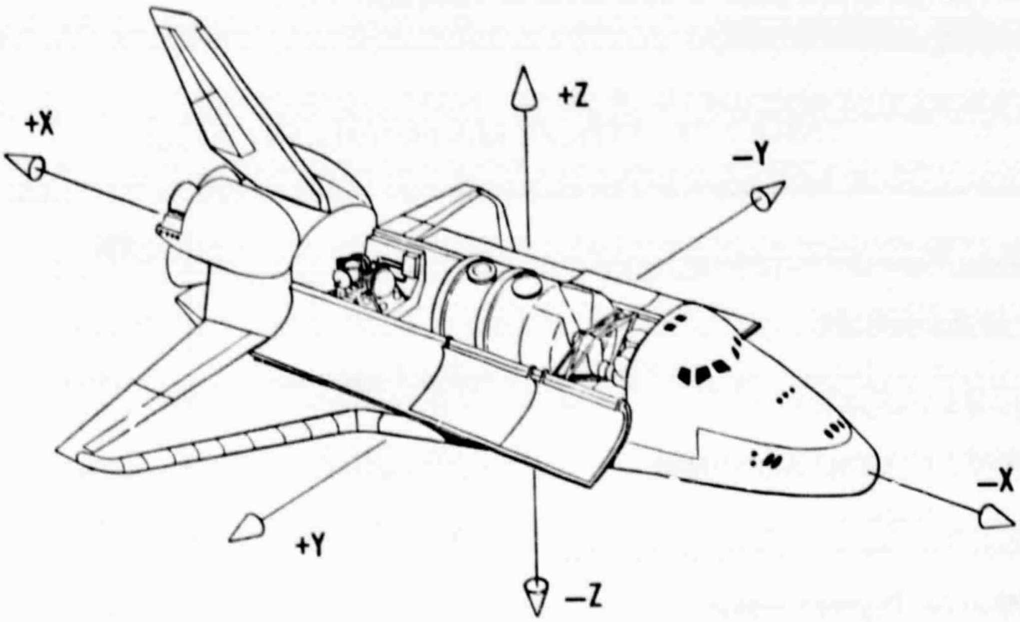


Figure 2-2 SPACE SHUTTLE COORDINATE SYSTEM

TABLE 2-IX TYPICAL RCS PROPELLANT USAGE FOR ORBITER TRANSLATIONAL MANUEVERS (Reference 18)

Translation Direction	Propellant Usage Kg/mps	(lb/fps)
+X	40.79	(27.4)
-X	40.12	(26.7)
+Y	66.20	(44.5)
-Y	66.41	(44.6)
+Z	31.29	(21.0)
-Z	55.17	(37.1)

The acceleration levels experienced by the Space Shuttle during coast for three different Shuttle orientations are shown in Figure 2-3. The coast gravitational level ranges from 3.8×10^{-7} g's to 3.0×10^{-6} g's for a 259 km (140 nautical mile) orbit.

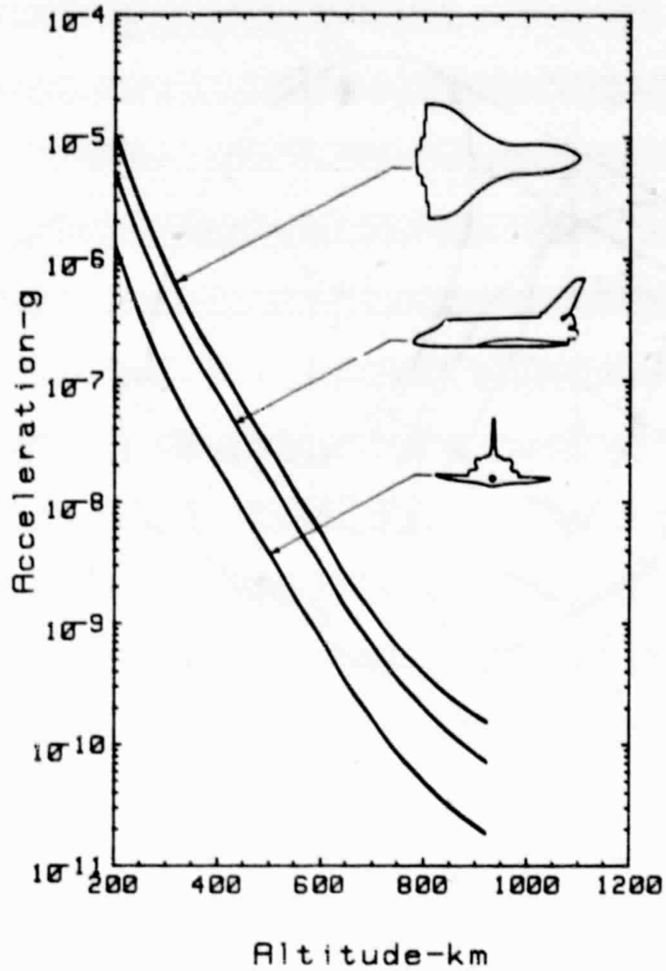


Figure 2-3 ACCELERATION LEVELS DURING COAST
(Reference 18)

The Spacelab pallet constraints are physical geometry, payload envelope and hardpoint locations. Figure 2-4 is a sketch of the Spacelab pallet illustrating the payload envelope pallet dimensions and pallet hardpoints. Pallet hardpoints are those points on the Spacelab pallet to which the facility hardware can be attached.

In addition to the Shuttle/Spacelab imposed constraints, the facility has to meet center of gravity, structural factors of safety, vibration loading and thermal requirements (Reference 18).

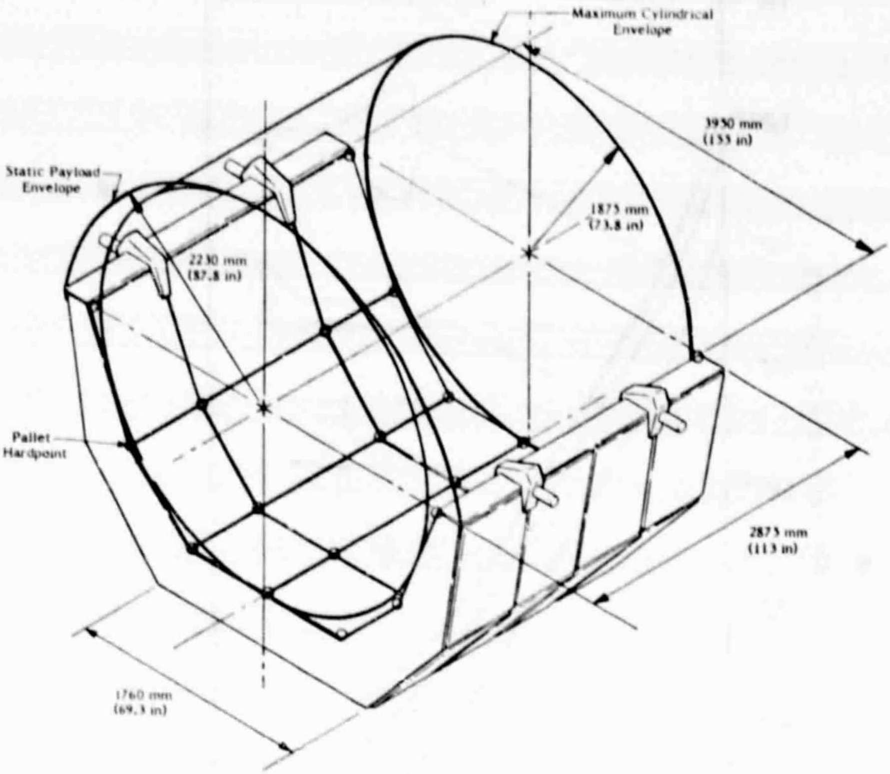


Figure 2-4 SPACELAB PALLET GEOMETRY

2.3.2 CFME Supply Tank Constraints. The statement of work for this study directed that the supply tank was to be the CFME tank being developed under NASA Contract No. NAS 3-21591. The supply tank is a 0.60 m^3 (21.19 ft^3) spherical tank and was originally selected to model, on a volume basis, a Space Shuttle Power Reactant Storage Assembly (PRSA) Hydrogen Tank. Table 2-X contains a breakdown of the liquid hydrogen quantity available in the supply tank. This table shows that approximately 34.24 Kg (75.50 lb) of liquid hydrogen is available for the facility receiver tank. The boiloff losses were determined by the heat leak given in Reference 3.

The maximum supply tank outflow rate, as indicated in Reference 20, is 22.7 g/sec (0.05 lb/sec). The supply tank is to provide vapor-free outflow for flow rates up to this maximum flow rate at a pressure not to exceed 414 kPa (60 psia).

In addition to the liquid quantity and maximum outflow rate constraints, the supply tank pallet mounting system was to be used.

TABLE 2-X SUPPLY TANK FLUID INVENTORY BREAKDOWN

Load at Launch (Minimum)	38.17 Kg	(84.16 lb)
Boiloff Over 3 Days at 44 gm/hr (0.097 lb/hr)	3.17 Kg	(6.98 lb)
2 Percent Residual	0.76 Kg	(1.68 lb)
TOTAL MASS AVAILABLE FOR TRANSFER	34.24 Kg	(75.50 lb)

Assumptions:

Vapor Pressure =	103.4 KPa	(15.0 psia)
Tank Volume =	0.60 m^3	(21.186 ft^3)
Residual Liquid =	0.27 Kg	(0.60 lb)
Initial Fill =	90%	

2.4 Receiver Tank Selections. The selection of receiver tanks to be used in the CFMF was based on experimental objectives, tankage configuration to be modeled and facility constraints. The four configurations given in Table 2-XI were considered.

The first configuration consists of using one 0.165 scale receiver tank for both phases of the facility. (All scaling is done on linear dimensions; i.e., length and diameter.) This receiver tank is the largest tank that can be filled with LH_2 from one CFME supply tank. This single tank concept is the lowest cost approach.

Configuration 2 consists of one 0.36 scale receiver tank for prechill and one 0.165 scale receiver tank for chill and fill. The 0.36 tank is the largest receiver tank which will fit on a single Spacelab pallet. This concept utilizes one CFME supply tank for both receiver tanks. The advantage to this configuration is the use of a larger receiver tank for prechill, thus providing scaling data superior to the 0.165 scale tank.

The third configuration consists of one 0.270 scale receiver tank and four CFME supply tanks. This concept represents the largest receiver tank which can be used for prechill, chill and fill, and fit on a single pallet. It represents the most costly approach due to the requirement of four supply tanks.

TABLE 2-XI FACILITY TANK ALTERNATIVES USING CFME SUPPLY TANKS

Configuration	Constraints	Advantages	Disadvantages
1. One CFME supply tank. One 0.165 scale POTV receiver tank.	Prechill, chill and fill can be accomplished with one CFME supply tank (receiver is the maximum size that can be filled with one CFME supply tank).	Experiment can be accomplished with a single set of tanks and therefore should be the lowest cost approach.	Scale of receiver tank for prechill is smallest.
2. One CFME supply tank. One 0.36 scale POTV receiver for prechill and one 0.165 scale POTV receiver for chill and fill.	Early experiments would use 0.36 scale POTV (largest receiver that will fit on a single pallet) for prechill testing. Later experiments would simulate chill and fill with a 0.165 scale receiver.	Allows largest size receiver that will fit on a single pallet to be used for prechill. Only requires a single supply tank.	Requires two separate receivers and would therefore be a more costly approach than configuration 1.
3. Four CFME supply tanks. One 0.27 scale POTV receiver tank.	Largest single receiver that can be used for all experiments given single pallet size constraints.	Allows single largest size receiver than can be prechilled, chilled and filled. Only requires a single receiver tank.	Requires four CFME supply tanks. May create feed system line chilldown problems that would require design of an accumulator tank. Results in the highest single pallet mission cost by utilizing entire pallet space for all missions.
4. One CFME supply tank. One 0.5 scale POTV receiver tank on two Spacelab pallets for prechill. One 0.165 scale POTV receiver for chill and fill.	Largest receiver tank which fits on two Spacelab pallets.	Largest receiver tank for prechill; permits scaling of pressure history, peak pressure and temperature.	Requires two Spacelab pallets during Phase I and thus highest mission cost.

The 0.5 scale receiver tank of Configuration 4 permits direct scaling of prechill results to the full scale POTV. The 0.165 scale tank would be used for chill and fill testing. This configuration results in the highest mission costs during Phase I due to the need for two Spacelab pallets.

A decision was made, following NASA review, to use Configuration 2 for the facility design. This choice represents a compromise between the lower cost of Configuration 1 and the technical advantages and higher costs of Configurations 3 and 4. The 0.36 and 0.165 scale tanks will be used for the Phase I and Phase II facility design, respectively.

2.5 Description of Transfer Processes. The objective of the experiment is to demonstrate the transfer of liquid propellant from a supply tank to a receiver tank. The approach described in the following paragraphs is consistent with the multiphase effort to be employed in the CFMF flights.

2.5.1 Supply Tank Pressurization. The baseline pressurization approach for the CFME supply tank is the use of helium supplied at ambient temperature. This approach

will be satisfactory providing that heat transfer between the warm helium and cold liquid or capillary device is minimized. Evaporation caused by heat transfer between the pressurant and LH_2 will increase hydrogen partial pressure and can make it difficult, if not impossible, to fill the receiver to a pressure below the receiver tank design allowable. Direct contact of warm pressurant with an impervious surface of the capillary device is likely to cause vapor to form within the capillary device channel. The use of ambient pressurant requires that relatively quiescent conditions exist in the supply tank from the time helium has been injected into the tank until all usable liquid has been expelled. If these conditions cannot be met, consideration should be given to using cryogenic helium pressurant to maintain low hydrogen partial pressures and prevent vapor formation in the capillary device.

2.5.2 Transfer Line Cooldown. A review of literature (References 21 through 26) was conducted to determine if pressure surges during transfer line cooldown would pose a problem for the POTV or the CFMF. Steward, Smith and Brennan (References 25 and 26) reported on liquid nitrogen and hydrogen transfer line cooldown. Their results indicate that transfer line chilldown pressure surges are enhanced by: (1) large mass flow rates, (2) high levels of liquid subcooling, (3) short valve opening times, (4) high density liquids and longer transfer lines. Based on these works, there exists no strong evidence that pressure surges will present a problem for the CFMF. The rate at which the supply tank outlet valve is opened can be limited during the initial prechill charges when the line is cooling down. Following transfer line cooldown, normal valve operation would be permitted.

The selected approach to transfer line cooldown for the CFMF is to flow the liquid through the transfer line, at low levels of subcooling, by slowly opening the supply tank outlet valve. If, during ground testing, pressure surges present a problem during transfer line cooldown, a possible solution would be to pre-cool the line utilizing the supply tank TVS flow. Two approaches were considered for such a back-up system: passing the cold vapor around the outside of the line in cooling coils or flowing the vapor directly through the line. Flowing outside the line minimizes valving requirements, but results in fabrication complexity. Internal flow requires additional valving to allow for cooldown fluid to enter and exit the transfer line.

2.5.3 Receiver Tank Fill. The approach proposed for accomplishing a no-vent receiver tank fill involves three phases: (1) prechill, (2) chill and (3) fill. This approach is designed to eliminate the need for venting while a two-phase mixture exists in the tank.

The receiver tank prechill process, beginning with the tank wall at some initial warm temperature, consists of a liquid charge, hold and vapor vent. The charge, hold and vent cycle is designed to prevent liquid from being vented overboard. Prechill continues until a predetermined tank wall temperature is reached. Prechilling the tank to this temperature permits chill and fill of the receiver tank without further venting. The prechill target temperature was determined using data obtained from Reference 8 and is plotted, as a function of tank scale, in Figure 2-5. During prechill, the flow into the tank is through an inlet manifold to provide high wall surface coverage by the impinging liquid and, thus, good heat transfer between the liquid and tank wall. Tank chill proceeds from the prechill target temperature to the saturation temperature of the fluid in the tank, whereupon the tank is filled. Tank chill and fill are both accomplished with the vent closed.

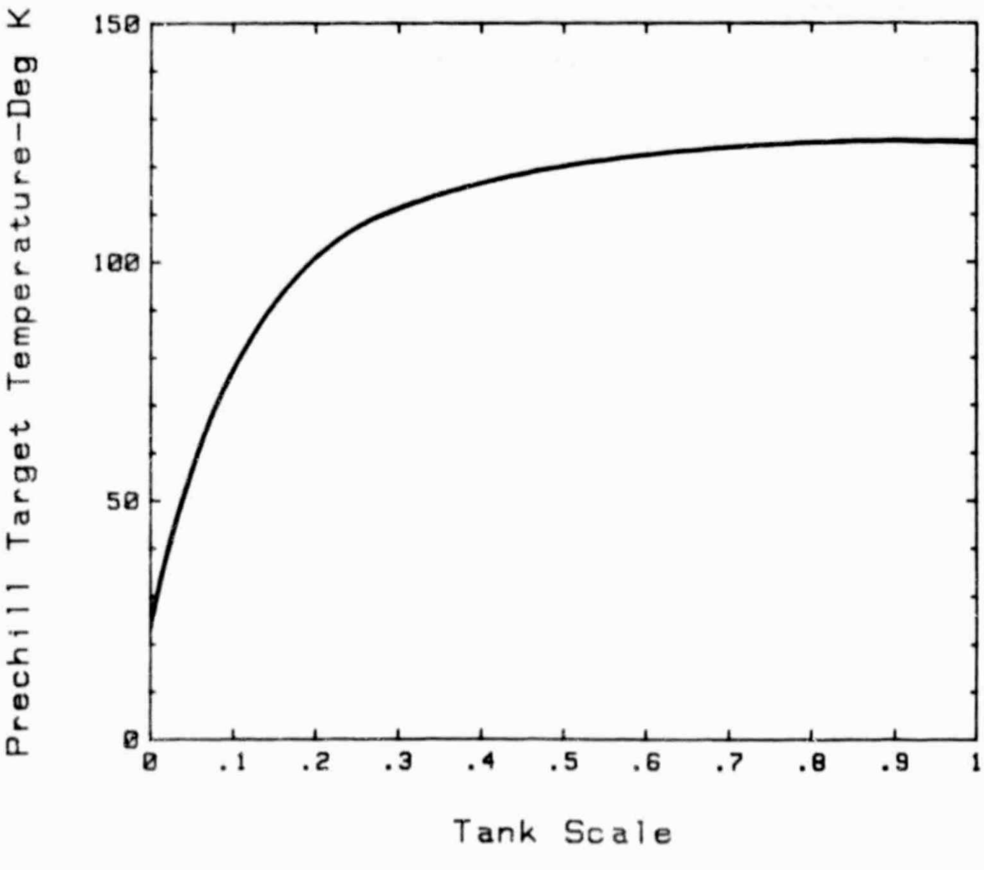


Figure 2-5 RECEIVER TANK PRECHILL TARGET TEMPERATURE VERSUS TANK SCALE

Inflow analyses were separated into prechill, chill and tank fill processes. The relationships for these processes, from the literature review, are summarized in Table 2-VI. Initially, during prechill, vapor will enter the tank from the warm line. The applicable equation for heat transfer between the incoming vapor and tank wall is:

$$\frac{h}{C_{pv}\,\rho_v}\ Pr_v^{\,2/3} = 0.13\left[\frac{(P/VO)\ \mu_v}{\rho_v^{\,2}}\right]^{1/4} \qquad \text{(Equation 2-1)}$$

where:

$$P = \eta\,\dot{m}\,V^2$$

When liquid enters the tank, the heat transfer between the liquid and vapor, and between the liquid and tank wall, must be considered.

Vapor-to-liquid heat transfer for evaporating drops is:

$$Nu = \frac{2 + 0.6\ Re_f^{\,1/2}\ Pr_f^{\,1/3}}{(1 + B)} \qquad \text{(Equation 2-2)}$$

where:

$$B = (h_v - h_{dv})/h_{fg}$$

For heat transfer between the liquid and tank wall, several relationships are applicable.

For quenching of spheres, the relationship governing film boiling heat transfer is:

$$Nu = 0.15\ Ra^{1/3} \qquad \text{(Equation 2-3)}$$

For liquids splattering on heated surfaces, the relationship is:

$$\frac{Q_{max}}{\rho_l\, d^3 \lambda} = 8.44 \times 10^{-3}\left[\frac{\rho_l^2\, V^2\, d}{\rho_{vf}\ \ g_c}\right]^{0.341} \qquad \text{(Equation 2-4)}$$

During receiver tank fill, when liquid and vapor exists in the tank, it is necessary to assess the mixing requirements in order to assure that thermodynamic equilibrium is maintained.

For tank mixing, at Bond numbers greater than 10:

$$V_o D_o > (h_m a/g_c)^{1/2} (Z - h_m) \qquad \text{(Equation 2-5)}$$

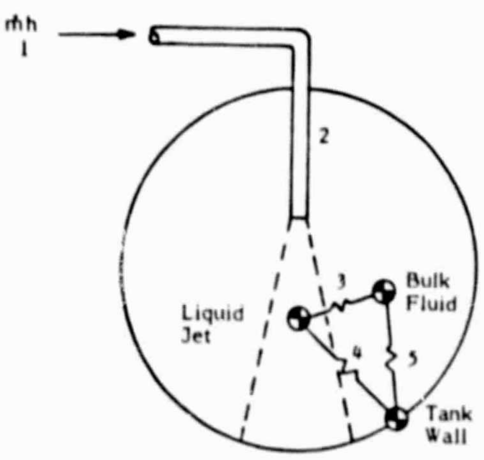
and for Bond numbers less than 10:

$$V_o D_o > Z^{1/2}/30 \qquad \text{(Equation 2-6)}$$

For heat transfer between the liquid and vapor during fill, Equation 2-1, evaluated using liquid properties, was used. A mixing time equation from Reference 12 was identified for use in the scaling analysis (Paragraph 2.6) and is:

$$\theta = \frac{5.2 \, d \, VO}{q \, (ZD)^{1/2}} \qquad \text{(Equation 2-7)}$$

The evaluation of the receiver tank thermodynamic processes was accomplished using the Beech developed Tank Cooldown Analysis Program (TNKCAP). The program incorporates the receiver tank model shown in Figure 2-6. The model contains nodes for the tank wall, fluid, incoming liquid and external environment. This model permits simulation of the receiver tank prechill, chill and fill processes. Thermodynamic fluid properties for hydrogen were determined by the equation-of-state given in Reference 28.



THERMODYNAMIC PROCESS

1. Mass Flow Into Tank = f (Δ P, f).
2. Isenthalpic Expansion.
3. Convective Heat Transfer From Liquid Drops to Bulk Fluid.
4. Heat Transfer Between Liquid Jet and Tank Wall:
   a. Nucleate Boiling
   b. Film Boiling
5. Heat Transfer Between Bulk Fluid and Tank Wall.

Figure 2-6 RECEIVER TANK THERMODYNAMIC MODEL

The relationships contained in Equations 2-1 through 2-4 were used to generate heat transfer coefficients for input to the receiver TNKCAP. The heat transfer coefficients used for prechill are:

Vapor to tank wall;

$h_f = 28.4\ w/m^2\text{-}^oK\ (5\ Btu/hr\text{-}ft^2\text{-}^oR)$ (from Equation 2-1)

Liquid to tank wall;

$h_f = 85.1\ w/m^2\text{-}^oK\ (15\ Btu/hr\text{-}ft^2\text{-}^oR)$ (from Equation 2-3)

Liquid to vapor;

$h_f = 300.8\ w/m^2\text{-}^oK\ (53\ Btu/hr\text{-}ft^2\text{-}^oR)$ (from Equation 2-2)

During filling, the liquid-vapor heat transfer, evaluated using liquid properties, is:

$h_f = 363.2\ w/m^2\text{-}^oK\ (64\ Btu/hr\text{-}ft^2\text{-}^oR)$ (from Equation 2-1)

The correlations of Reference 27 (Equations 2-5 and 2-6) were used to predict liquid jet requirements to promote mixing and thermal equilibrium during tank fill.

The prechill charge is initiated by flowing hydrogen through the receiver tank fill manifold until the tank pressure reaches a predetermined value (designated the charge termination pressure). The charge termination pressure is lower than the pressure selected for vent initiation, which is chosen to be close to the maximum working pressure. The difference between the charge termination and vent initiation pressures determines the maximum amount of energy that can be removed during any single charge, hold and vent cycle. Initiation of the vent portion of the cycle is based upon either the vent initiation pressure, or the difference between the average tank wall temperature and the average fluid temperature. If the average fluid temperature equals or exceeds 95 percent of average tank wall temperature, the vent is opened until the vent termination pressure is reached. This method of operating the vent ensures that liquid is not vented and prevents excessive prechill times by eliminating the need to wait for thermal equilibrium. Table 2-XII contains the charge, hold and vent pressures for the 0.165 and 0.36 scaled receiver tanks.

TABLE 2-XII PRECHILL CHARGE, HOLD AND VENT PARAMETERS

Parameter	0.36, Phase I KPa	(psia)	0.165, Phase II KPa	(psia)
Charge Termination Pressure	103.4	(15.0)	137.9	(15.0)
Vent Initiation Pressure	241.3	(35.0)	241.3	(35.0)
Vent Termination Pressure	10.3	(1.5)	10.3	(1.5)

Based on the heat transfer coefficients presented and the prechill operational parameters (i.e., charge termination, vent initiation and vent termination pressures), the receiver tank computer model was used to predict temperature and pressure histories for both the Phase I and Phase II receiver tanks. It was assumed that good mixing between the bulk liquid and vapor existed to promote thermal equilibrium. Figures 2-7 and 2-8 show the temperature and pressure histories for Phase I and Phase II receiver tanks, respectively. These figures show that three prechill cycles are required for the Phase I receiver tank and six prechill cycles are required for the Phase II receiver tank.

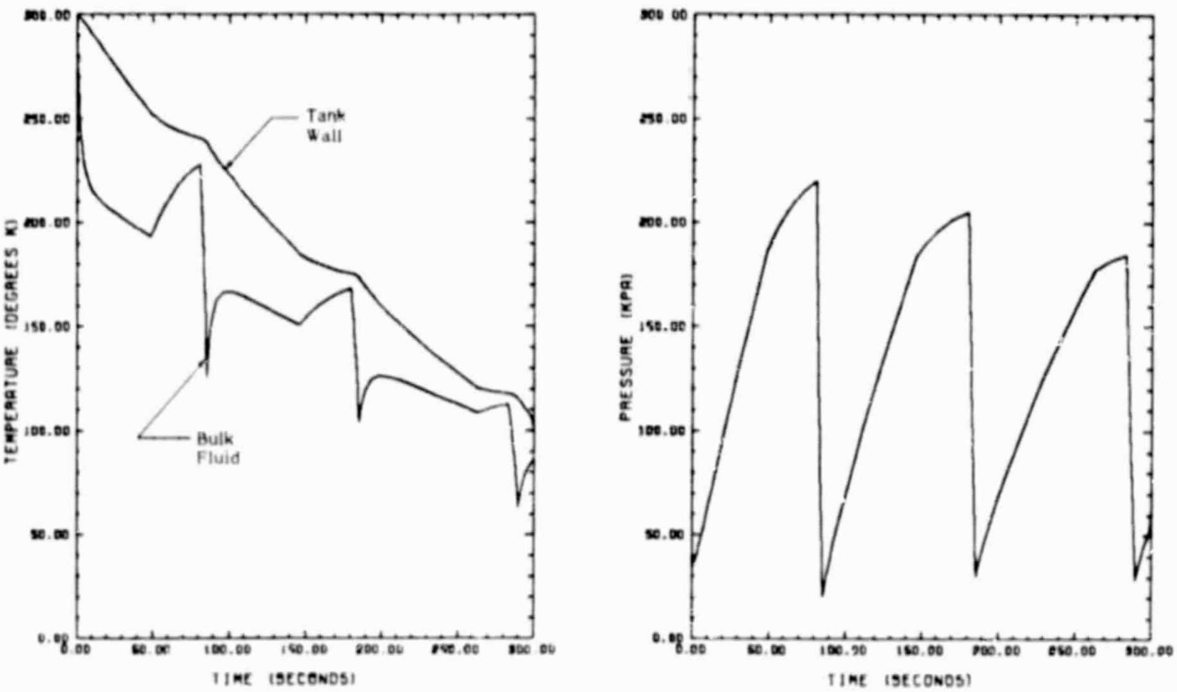


Figure 2-7 PHASE I RECEIVER TANK TEMPERATURE AND PRESSURE HISTORIES

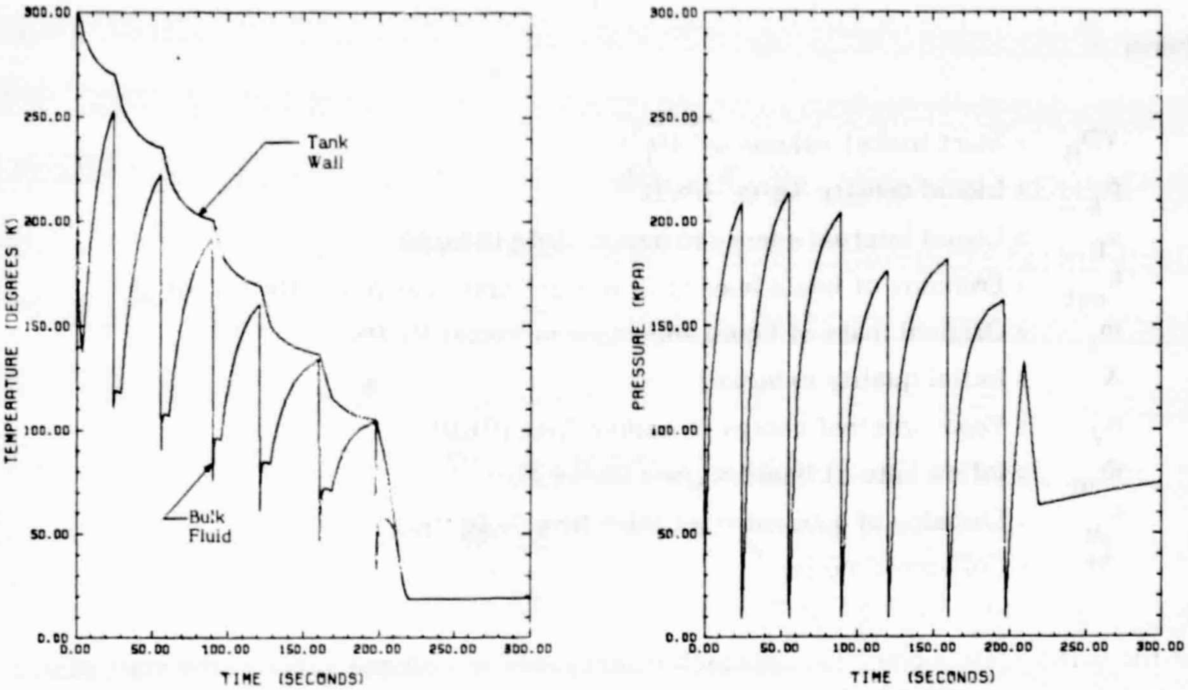


Figure 2-8 PHASE II RECEIVER TANK TEMPERATURE AND PRESSURE HISTORIES FOR PRECHILL, CHILL AND FILL

2.5.4 Start Basket Vapor Collapse. Filling of the start basket will be accomplished by flowing a portion of the subcooled inlet fluid through the start basket outlet (i.e., back filling). An analysis in Reference 1 indicated that an inlet flow equivalent to four jets would be sufficient to condense any trapped vapor during filling the Phase II receiver tank.

The active bubble collapse time is a function of basket volume, degree of subcooling, fraction of trapped vapor and inflow rate to the basket. This relationship is given by Equation 2-8.

$$\Delta t = \frac{VO_B\ \rho_L\ (u_L - h_{out}) - m_i\ (X\ u_V + (1 - X)\ u_L - h_{out})}{\dot{m}_{in}\ (h_{in} - h_{out})} \qquad \text{(Equation 2-8)}$$

where:

VO_B	= Start basket volume m^3 (ft^3)
ρ_L	= Liquid density Kg/m^3 (lb/ft^3)
u_L	= Liquid internal energy in basket J/Kg (Btu/lb)
h_{out}	= Enthalpy of liquid leaving at initial basket condition J/Kg (Btu/lb)
m_i	= Original mass of liquid and vapor in basket Kg (lb)
X	= Initial quality in basket
u_V	= Vapor internal energy in basket J/Kg (Btu/lb)
$\dot{m}_{in}$	= Inflow rate of liquid Kg/sec (lb/sec)
h_{in}	= Enthalpy of subcooled jet inlet flow J/Kg (Btu/lb)
Δt	= Collapse time (sec)

For the 0.165 scale model, the approach investigated to collapse vapor in the start basket was to flow 22 percent of the inlet flow through the start basket outlet and channels into the basket to condense the trapped vapor. As shown in Figure 2-9, using the equivalent flow from four jets will result in collapse times (using Equation 2-8) of approximately one minute. This assumes that four vapor bubbles of 54.6 mm diameter (2.15 in) were trapped between the channels, the mass flow rate from each jet is 1.26 g/sec (0.0028 lb/sec) and the tank liquid is saturated at 138 KPa (20 psia).

Passive bubble collapse was evaluated for the largest possible bubble present in the start basket following fill. The following relationships (from Reference 17) were used to calculate the collapse times.

For a spherical bubble with radial motion:

$$\tau_H = \frac{1}{3}\left(\frac{2}{\alpha} + \alpha^2 - 3\right) \qquad \text{(Equation 2-9)}$$

and for a plane interface (neglecting bubble curvature and convective heat transfer):

$$\alpha = 1 - \tau_H^{1/2} \qquad \text{(Equation 2-10)}$$

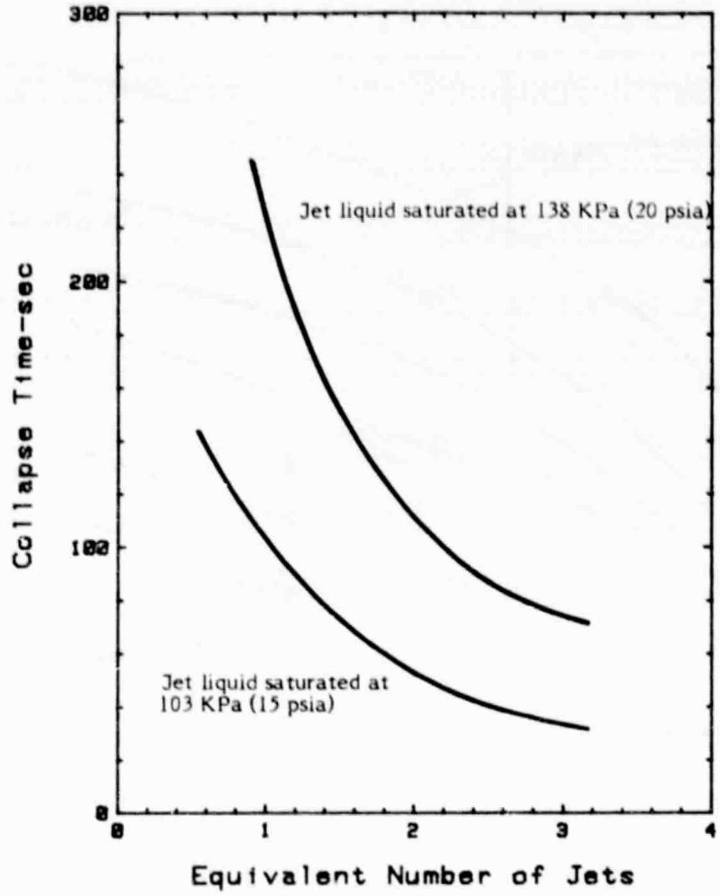


Figure 2-9 ACTIVE VAPOR COLLAPSE USING LIQUID FLOW INTO START BASKET (0.165 SCALE)

where:

$$\tau_H = 4\pi Ja^2 \frac{\alpha t}{R_o^2}$$

(See Table 2-IV for nomenclature.)

Figure 2-10 illustrates the relationship between tank pressure subcooling and vapor collapse times given by Equations 2-9 and 2-10. The maximum size of a trapped bubble for a 0.165 scale model start basket is shown by the vertical line in Figure 2-10. These collapse times are on the order of hours as opposed to minutes for active collapse (Figure 2-9).

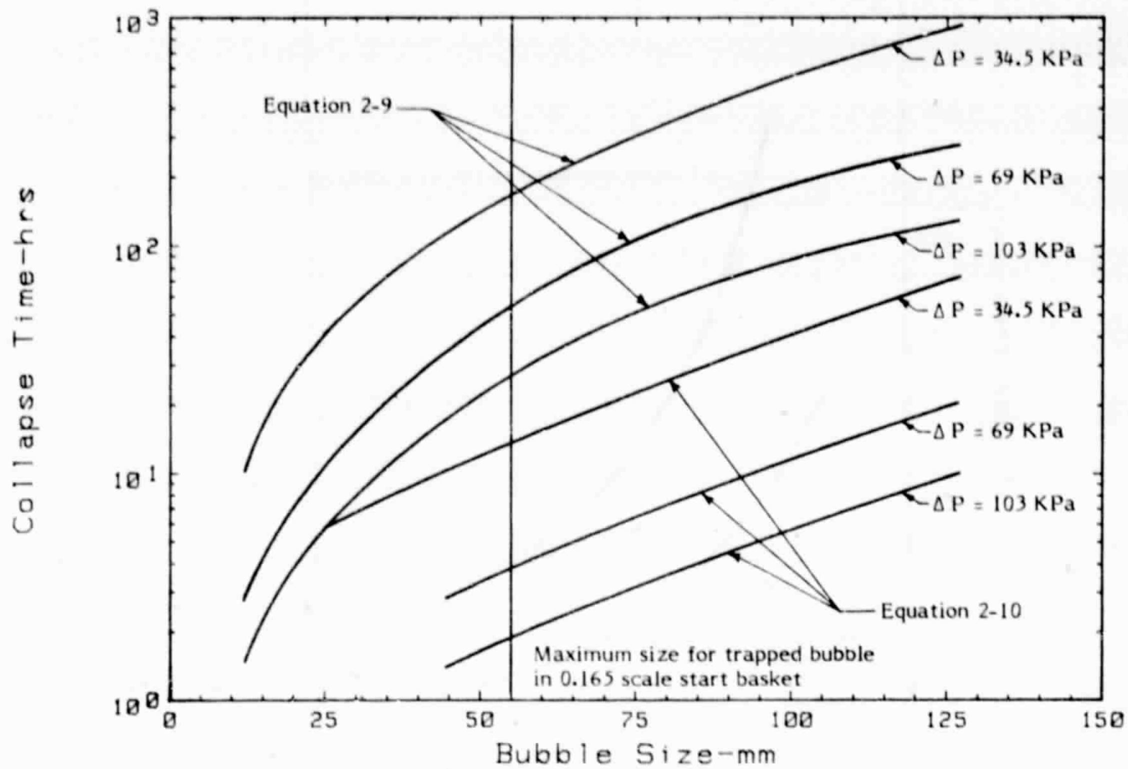


Figure 2-10 BUBBLE SIZE VERSUS COLLAPSE TIME
(PASSIVE BUBBLE COLLAPSE)

2.5.5 Venting. It must be demonstrated that helium can be removed from a partially filled LO_2 or LH_2 POTV tank. As reported in Reference 1, this is required to prevent overpressurization of the tank during refill. The technology to accomplish helium venting will be demonstrated in this experiment.

Two approaches to helium venting were considered: The first approach (active) utilizes the primary RCS thrusters to settle the liquid in the receiver tank during which time venting occurs; the second approach (passive) will use a tapered vent tube (Figure 2-11) to separate the liquid and vapor phases.

The vent tube operates by shedding most of the liquid which is in contact with the tube surface. Small amounts of liquid may be trapped inside the tube prior to venting, but will have a negligible effect on overall vented fluid quantity if the bulk liquid resides in a "normal" low-gravity position as shown in Figure 2-11.

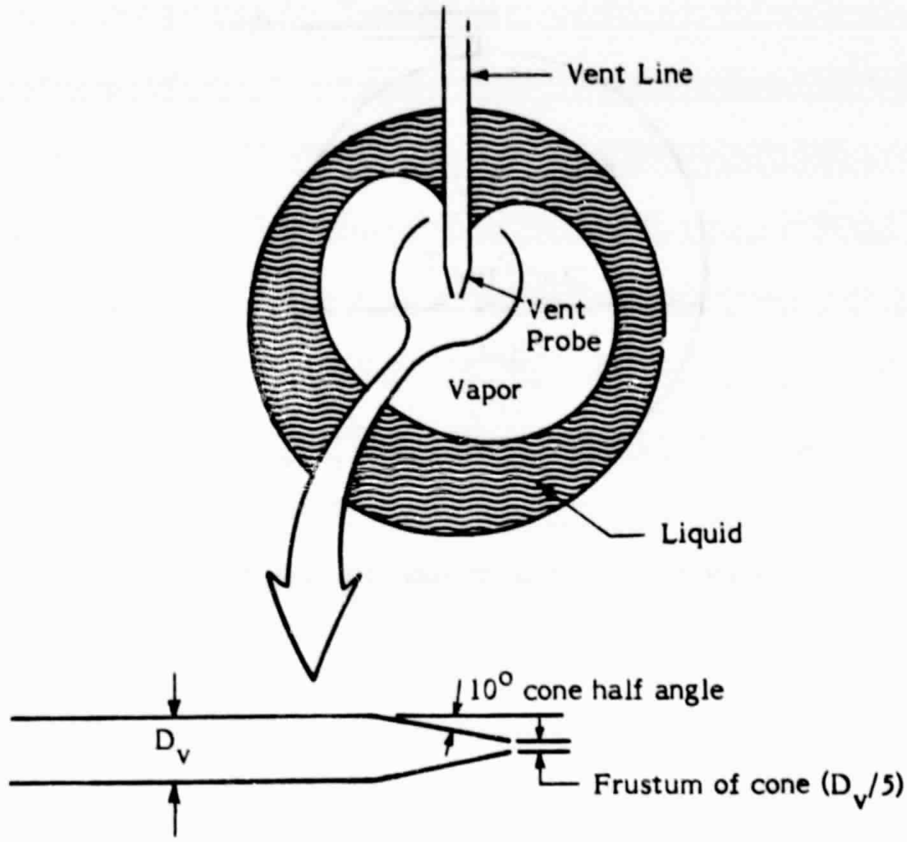


Figure 2-11 VENT TUBE LOCATION AND CONFIGURATION

An analysis was conducted to determine partial pressures of hydrogen and helium in the tank during venting. It was assumed that psuedo-equilibrium conditions exist in the tank. This assumption implies that vent flow rates be sufficiently small so that hydrogen boil-off occurs at a rate appproximately equal to quantity of hydrogen vented. However, the amount of hydrogen boiled off is slightly lower than the amount vented, due to liquid cooling, resulting in a reduced partial pressure of the hydrogen. This analysis assumes, therefore, that the hydrogen partial pressure is the saturation pressure based on the liquid hydrogen temperature.

The model employed in this analysis is shown in Figure 2-12. Calculations using a half-full Phase II receiver tank produced results showing the average tank temperature, total tank pressure, and helium and hydrogen partial pressure (Figure 2-13) histories assuming a 22.7 gm/sec (0.05 lb/sec) vent outflow rate.

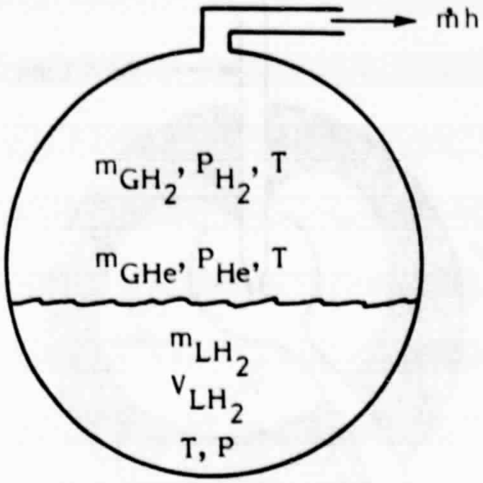


Figure 2-12 HELIUM VENTING MODEL

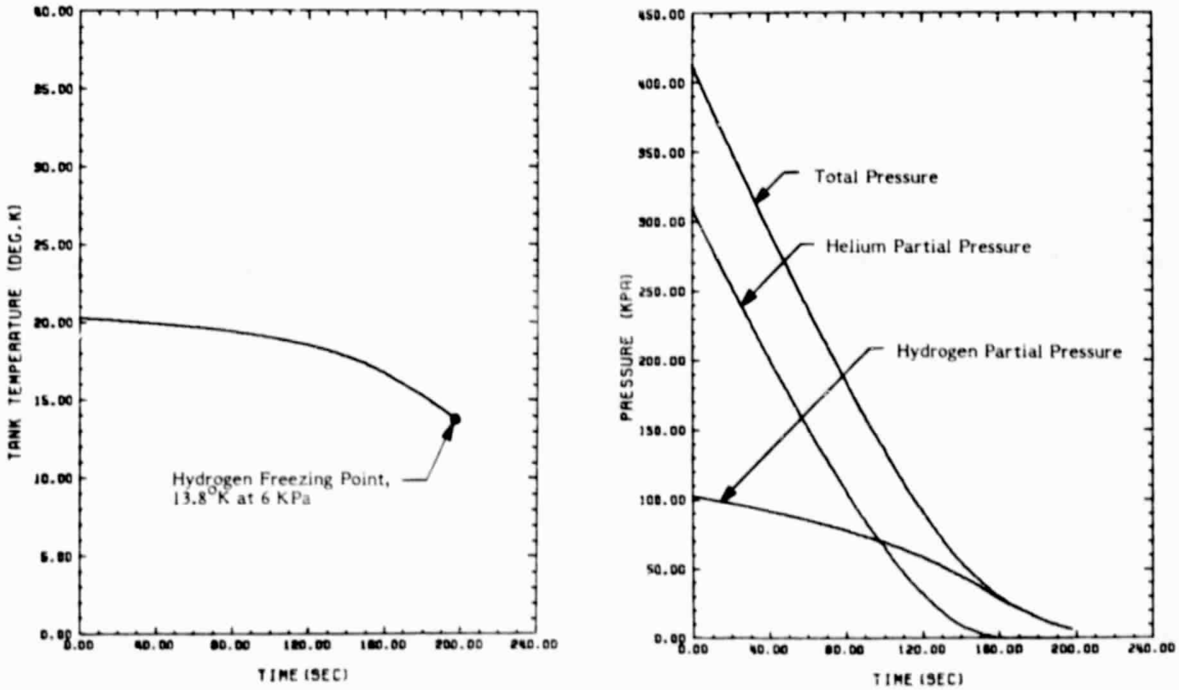


Figure 2-13 RECEIVER TANK TEMPERATURE AND PRESSURE HISTORIES DURING VENT

2.5.6 Receiver Tank Pressurization. Receiver tank pressurization will be accomplished using ambient helium injected into the tank. Pressurization considerations have been evaluated only to the degree to which they affect experiment objectives of capillary device thermal conditioning and refilling of a partially full tank. Interactions of liquid/vapor mixing subsequent to pressurization and resultant pressure history and capillary device evaporation on bulk boiling considerations should be part of the detailed design to characterize pressurant injection location and temperature requirements for an actual POTV case.

During detailed design of the experiment, an assessment of the current state of development of the POTV should be made to determine if autogeneous pressurization is feasible. If it is, then autogeneous pressurization testing may be included in the experiment.

2.6 Scaling Analysis. An analysis was conducted to determine if the data obtained from the Phase I and Phase II receiver tanks could be scaled to the prototype tank (POTV). The series of curves given in Figure 2-14 were constructed, using data presented in Reference 8, showing the dry tank mass, wetted mass and total mass as a function of tank scale for the prototype tank. Tank scale or scale factor, is defined as the ratio of model to prototype tank dimensions. Dry tank mass is the mass of the pressure vessel; the wetted mass is the dry tank mass plus the mass of the internal components; the total mass is the wetted mass plus the insulation, external structure and hardware.

The model receiver tank allowable pressure, as a function of tank scale, is shown in Figure 2-15. At a constant pressure (172.4 KPa (25 psia) for the prototype), the model tank wall thickness decreases as the scale factor decreases until the minimum wall thickness of 0.635 mm (0.025 in) is reached. (This is the minimum wall thickness that can be welded.) At this point allowable model tank pressure increases as scale factor decreases. At a scale factor of unity, the model tank wall thickness exceeds the prototype wall thickness, because the selected model tank material, 6061-T6 aluminum, has a lower ultimate strength than the POTV material, 2219-T87 aluminum. 6061 aluminum was selected because it exhibits superior weldability and corrosion resistance than does 2219.

Scaling parameters discussed in Reference 1 are plotted as a function of tank scale in Figure 2-16 (P*, V* and M* represent the ratio of model to prototype pressure, volume and wetted mass, respectively). To produce these plots, tank volumes for both the model

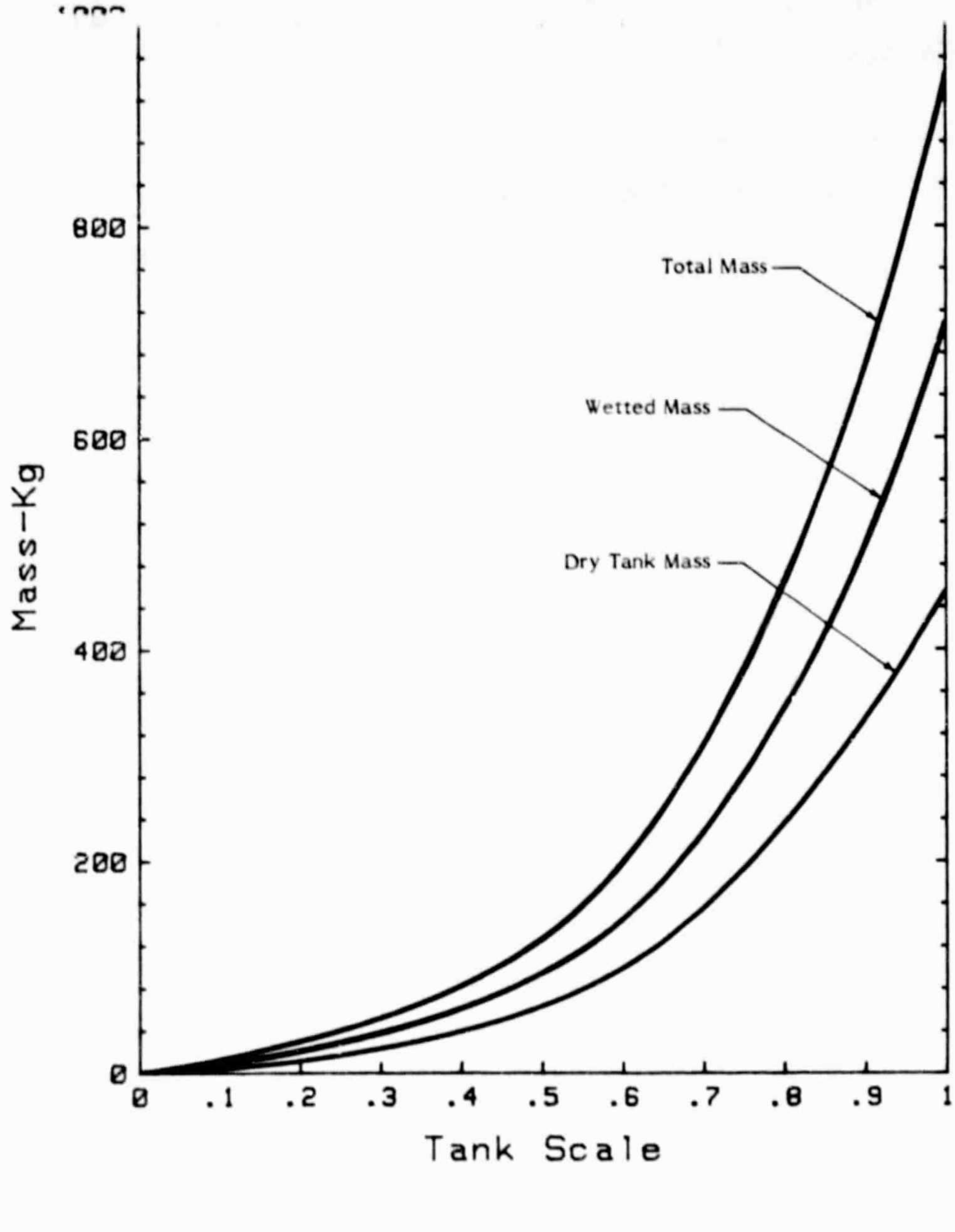


Figure 2-14 RECEIVER TANK MASS CHARACTERISTICS VERSUS TANK SCALE

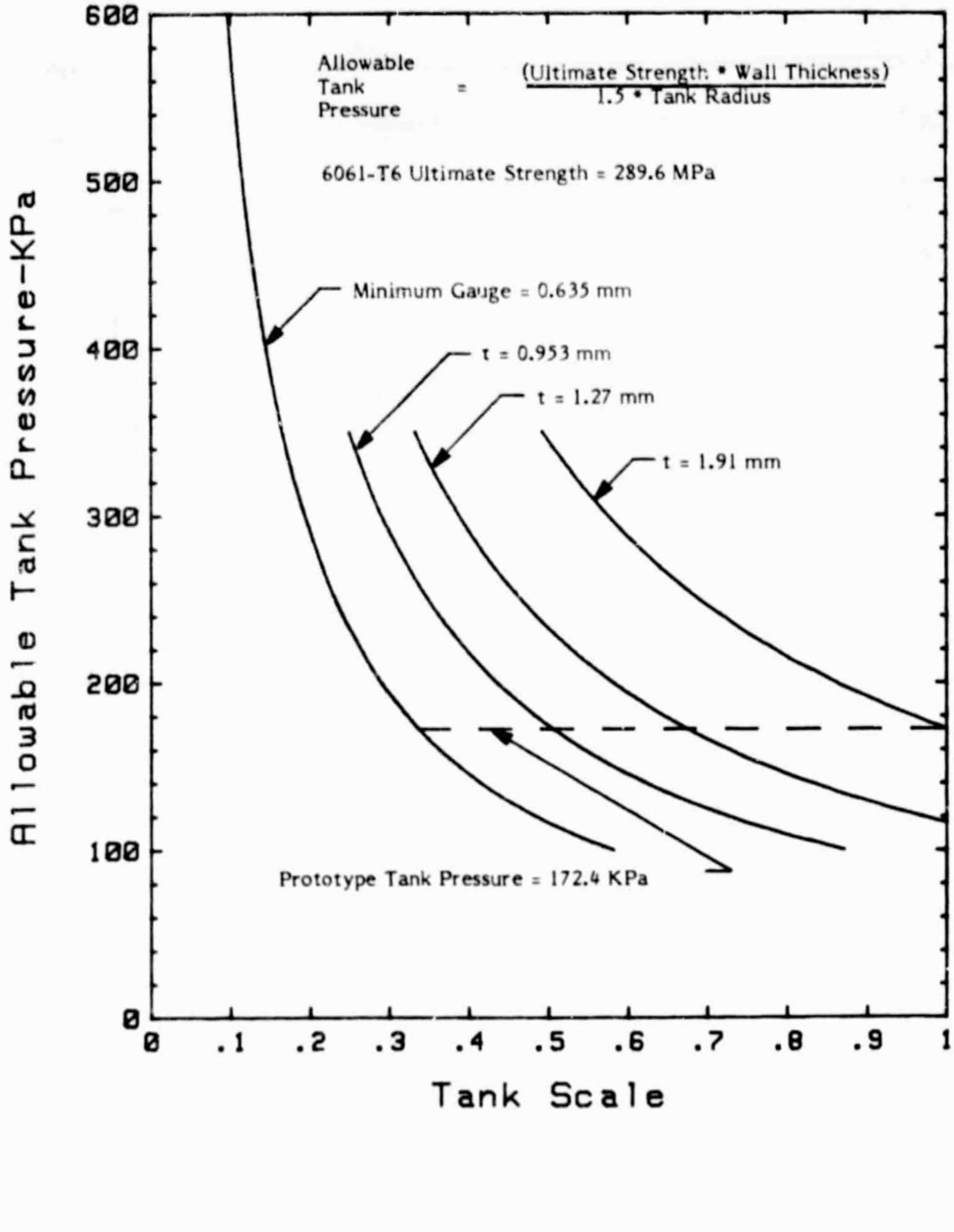


Figure 2-15 ALLOWABLE RECEIVER TANK PRESSURE VERSUS TANK SCALE

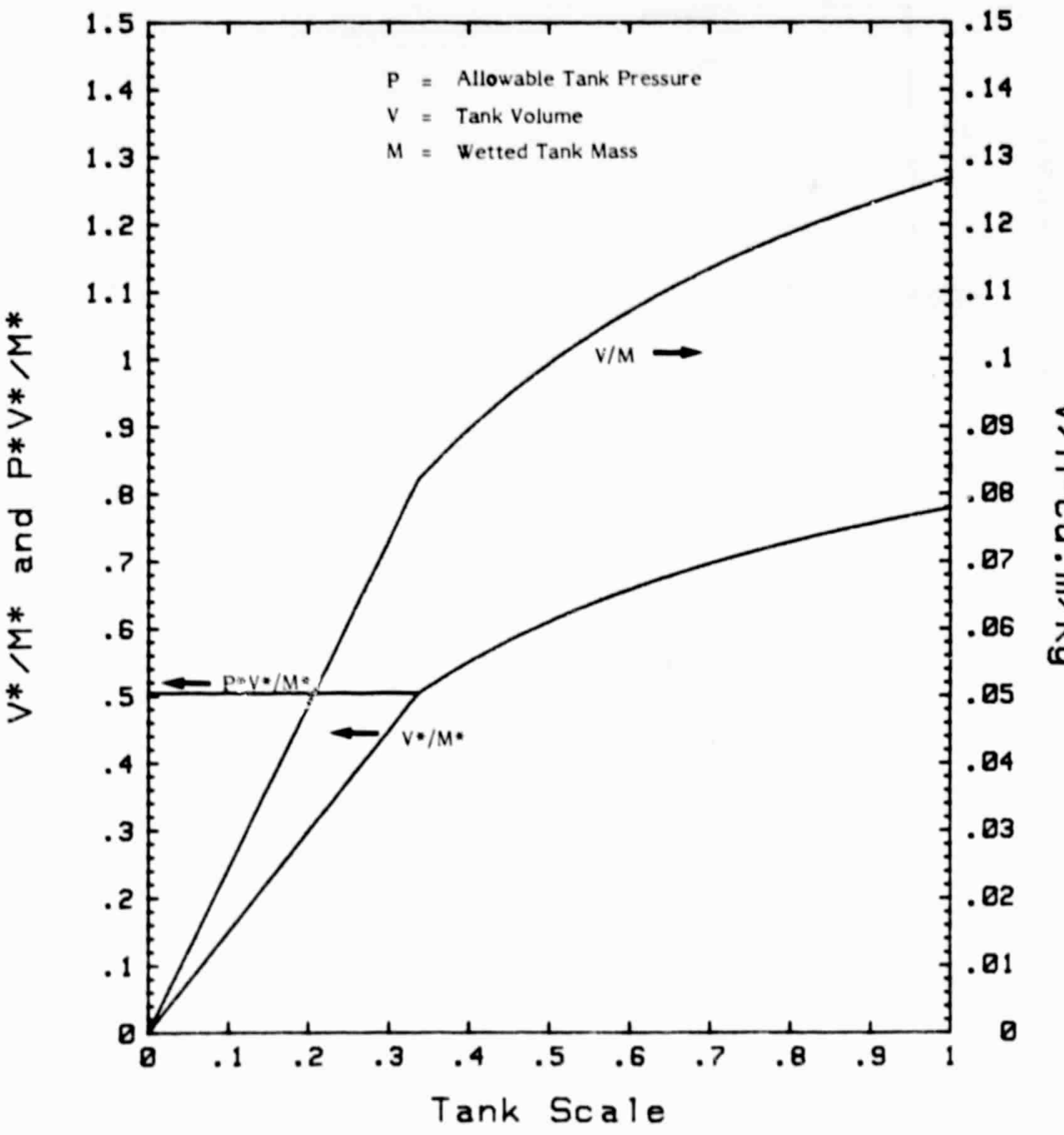


Figure 2-16 PRECHILL SCALING PARAMETERS VERSUS TANK SCALE

and prototype are calculated from the geometric relationships using the appropriate scaled tank dimensions for the model; dry tank masses are calculated from tank surface area and wall thickness; the mass of the model tank internal components is assumed to vary with the square of the model tank radius and is assumed to be equal to the internal components mass of the prototype tank when the model and prototype radii are equal (i.e., tank scale = 1). The break in the three curves at a scale factor of approximately 0.34 occurs at the point of minimum model tank wall thickness. At scale factors larger than this, model tank pressure is assumed equal to prototype tank pressure, and model tank wall thickness increases linearly with increasing tank scale. Thus, the V^*/M^* and P^*V^*/M^* curves coincide in this range because $P^* = 1$. At scale factors below 0.34, model tank pressure increases at the same rate as V^*/M^* decreases. Consequently, P^*V^*/M^* = constant as scale factor approaches 0. At a scale factor of 1, V^*/M^* and P^*V^*/M^* do not reach unity, again because the model tank wall is thicker than the prototype, causing M^* to be greater than 1.

The plots in Figure 2-16 illustrate that exact P^*V^*/M^* or V^*/M^* scaling is not possible. If 2219-T87 aluminum were used in model tank construction, P^*V^*/M^* and V^*/M^* would be closer to unity at the higher scale factors, allowing nearly exact scaling at these conditions. However, the Phase I and II receiver tank scales of 0.36 and 0.165, respectively, are so low that exact scaling would not be possible even if the model tank were constructed with 2219. Since exact scaling is not possible, the experiment was designed to maintain similar flow and heat transfer regimes between model and prototype so that the same analytical expressions will apply to both the prototype and the model (i.e., similarity scaling).

The relationships governing the transfer processes were identified in Table 2-VI. The initial consideration was to determine which of these equations applied to the POTV transfer processes. The second consideration was the modeling constraints imposed on experiment conditions if the relationship were to be scaled from prototype to model. The final consideration was the regimes over which the equations were applicable for the POTV and whether model conditions could be maintained within these regimes.

Of the equations from Table 2-VI, Perry and Chilton (Reference 32) and Bromley (References 29 and 30) were found not to be applicable to the POTV. For film boiling, scaling analysis indicated that Berenson (Reference 11) did not set regime limits and only

required maintenance of equivalent g levels between model and prototype. For evaporation of drops, Yuen and Chen (Reference 14) were selected over Eisenklam (Reference 31) because of its greater applicability to the anticipated model velocity range. The equations, along with their limits for satisfying the regime requirements, selected for use in the scaling analysis are given in Table 2-XIII.

Exact scaling relationships were determined by setting each equation of Table 2-XIII equal to itself for both prototype and model conditions. Fluid properties in the model and prototype are assumed to be identical. Additional constraints include:

Ratio of tank diameters $D_m/D_p = 0.165$
Model tank diameter (Phase II) $D_m = 0.69$ m (2.28 ft)
Maximum supply tank outflow rate $\dot{m}_m = 22.7$ g/sec (0.05 lb/sec)
Prechill: Prototype inlet velocity $V_p = 3.3$ m/sec (11 ft/sec)
Prototype mass flow rate $\dot{m}_p = 0.45$ Kg/sec (1 lb/sec)
Fill: Prototype inlet velocity $V_p = 6.7$ m/sec (22 ft/sec)
Prototype mass flow rate $\dot{m}_p = 0.91$ Kg/sec (2 lb/sec)

Evaluation of the exact scaling relationships yielded conflicting model inflow velocity and jet diameters. For example:

1. The jet orifice diameters required to model a typical POTV with a liquid inflow velocity of 0.56 m/sec (1.83 ft/sec) are:

    Yuen and Chen, evaporating drop - 0.61 mm (0.002 ft)
    McGinnis, boiling drops - 4.56 mm (0.015 ft)
    Okita and Oyama, mixing - 17.6 mm (0.00579 ft)

2. Table 2-XIII (column titled: Model Constraints for Scaling) shows conflicting velocity requirements will result from exact scaling constraints using a fixed jet diameter.

With the inability to utilize exact scaling, a similarity scaling technique was employed which consisted of maintaining similar heat and mass transfer regimes. Table 2-XIII (column titled: Limits of Model Conditions Required to Maintain Similar Regimes) contains a summary of velocity constraints for similarity scaling analysis.

TABLE 2-XIII SUMMARY OF SC

Period	Condition/Reference	Equation	Limits of Equation	POTV Range	Scaling Re
Prechill	Film Boiling, Quenching of Spheres, Frederking and Clark, Reference 15	$Nu = 0.15\ Ra^{1/3}$	$Ra > 5 \times 10^7$	$4 \times 10^8 < R_a < 3 \times 10^{16}$	$a/g_o\ m$
Prechill	Film Boiling, Giarratano and Smith, Reference 16	$\ln Y = -0.185 - 0.251 \ln X - 0.00767 (\ln X)^2$ $Y = Nu_e / \left(0.026\ Re_v^{0.8}\ Pr_v^{1/3} \left(\frac{\mu_v}{\mu_w}\right)^{0.14}\right)$	$0.07 < \left(\frac{1-X}{X}\right)^{0.9} \left(\frac{\rho_v}{\rho_l}\right)^{0.5} \left(\frac{\mu_l}{\mu_v}\right)^{0.1} < 70$	Limited to $0.016 < X < 0.97$ to satisfy limits	$V_m^{0.8} = ($
Prechill	Evaporating Drops in Vapor, Yuen and Chen, Reference 14	$Nu = \frac{2 + 0.6\ Re_f^{1/2}\ Pr_f^{1/3}}{1 + B}$ $B = (h_v - h_{dv})/\lambda$	$B \sim 0.5$ $200 < Re < 2000$	$0 < B < 8.25$ $157 < Re < 10924$ $B = 0.5$ at $T_v - 38^oK\ (68^oR)$	$2 + 0.6$
Prechill	Boiling Drops Impinging On Surfaces, McGinnis and Holman, Reference 13	$\frac{Q_{max}}{\rho_l d^3 \lambda} = 8.44 \times 10^{-3} \left(\frac{\rho_l^2 V^2 d}{\rho_{vf}\, \sigma\, g_c}\right)^{0.341}$	$\frac{\rho_l^2 V^2 d}{\rho_{vf}\, \sigma\, g_c} < 3 \times 10^7$	$7 \times 10^4 < \frac{\rho_l^2 V^2 d}{\rho_v\, \sigma\, g_c} < 5.4 \times 10^5$	$V_m^{0.682}$
Prechill	Vapor Flow Onto Tank Wall, Uhl and Gray, Reference 12	$\frac{h}{C_{p_v} \rho_v} Pr_v^{2/3} = 0.13 \left(\frac{P/VO\ \mu_v}{\rho_v^2}\right)^{1/4}$ $P = \eta\, \dot{m}\, V^2 = 0.4\, \dot{m}\, V^2$	$3 \times 10^{-6} < \left(\frac{P/VO\ \mu_v}{\rho_v^2}\right)^{1/4} Pr_v^{-2/3} < 6.6$	$\left(\frac{P/VO\ \mu_v}{\rho_v^2}\right)^{1/4} Pr_v^{-2/3} < 1.7$	$\dot{m}_m\ V_m^2$
Fill	Vapor to Liquid Heat Transfer, Uhl and Gray, Reference 12	$\frac{h}{C_{p_l} \rho_l} Pr_l^{2/3} = 0.13 \left(\frac{P/VO\ \mu_l}{\rho_l^2}\right)^{1/4}$ $P = \eta\, \dot{m}\, V^2 = 0.4\, \dot{m}\, V^2$	$3 \times 10^{-6} < \left(\frac{P/VO\ \mu_l}{\rho_l^2}\right)^{1/4} Pr_l^{-2/3} < 6.6$	$\left(\frac{P/VO\ \mu_l}{\rho_l^2}\right)^{1/4} Pr_l^{-2/3} - 0.019$	$\dot{m}_m\ V_m^2$
Fill	Destratification, Poth and Van Hook, Reference 27	$V_o\, d_o > (h_m\, a/g_c)^{1/2} (Z - h_m)$ $V_o\, d_o > Z^{1/2}/30$ for LH_2	$Bo > 10$ $Bo < 10$	$Bo > 10$, for $a/g_c > 3 \times 10^7$ Not generally applicable for POTV	$d_m = (L$ when h_m
Fill	Mixing Time, Okita and Oyama, Reference 30	$\theta\, q/VO = \frac{5.2\, d}{(ZD)^{1/2}}$	$Re > 10^3$	$Re = 1.3 \times 10^5$	$\frac{d}{D}\ \frac{VO}{\dot{m}}$

FOLDOUT FRAME

II SUMMARY OF SCALING ANALYSIS

	Scaling Relationship	Model Constraints For Scaling	Limits of Model Conditions Required To Maintain Similar Regimes
$\times 10^{16}$	$a/g_{o\,m} = a/g_{o\,p}$	Not velocity dependent, only a function of a/g_o and T_w.	Applicable below 131°K (235°R) at 1×10^{-4} g's
$< X < 0.97$	$V_m^{0.8} = \left(\frac{D_m}{D_p}\right)^{0.2} V_p^{0.8}$	$D_m/D_p = 0.165$, $V_p = 3.4$ m/sec (11 ft/sec) $V_m = 2.1$ m/sec (7 ft/sec)	$0.016 < X < 0.97$
°K (68°R)	$\frac{2 + 0.6\, Re_m^{1/2}}{d_m} Pr_m^{1/3} = \frac{2 + 0.6\, Re_p^{1/2}}{d_p} Pr_p^{1/3}$	At $V_p = 3.4$ m/sec (11 ft/sec) and $d_p = 32$ mm (0.0104 ft) $V_m^{0.5} = 35\, d_m^{0.5} - \frac{0.026}{d_m^{0.5}}$	At 38°K for $8.71 \times 10^{-4} < V_m d_m < 8.71 \times 10^{-3}$ m²/sec (At 68°R for $0.00938 < V_m d_m < 0.0938$ ft²/sec)
$< 5.4 \times 10^5$	$V_m^{0.682} = V_p^{0.682} \left(\frac{d_p}{d_m}\right)^{3.341} = \frac{1.02 \times 10^{-8}}{d_m^{3.341}}$	$d_m^{3.341} V_m^{0.682} = 1.02 \times 10^{-8}$	$V_m^2 d_m < 2.0$ m³/sec ($V_m^2 d_m < 71$ ft³/sec)
$^{-2/3} < 4.7$	$\dot{m}_m V_m^2 = 4.49 \times 10^{-3} \dot{m}_p V_p^2$	$\dot{m} V_m^2 = 2.28 \times 10^{-2}$ m²-Kg/sec² (0.54 ft²-lb/sec²) $V_m = 1.0$ m/sec (3.3 ft/sec)	$9.5 \times 10^{-9} < V_m < 1.2 \times 10^3$ m/sec ($3.1 \times 10^{-8} < V_m < 3.8 \times 10^3$ ft/sec)
$Pr_l^{-2/3} - 0.019$	$\dot{m}_m V_m^2 = 4.49 \times 10^{-3} \dot{m}_p V_p^2$	$\dot{m} V_m^2 = 0.188$ m²-Kg/sec (4.45 ft²-lb/sec²) $V_m = 2.84$ m/sec (9.32 ft/sec)	$5.9 \times 10^{-8} < V_m < 2.9 \times 10^5$ m/sec ($1.94 \times 10^{-7} < V_m < 9.4 \times 10^5$ ft/sec)
$g_c > 3 \times 10^7$ applicable for POTV	$d_m = (L_p/L_m)^2 d_p$ when $h_m = d_m$ and $a/g_{o\,m} = a/g_{o\,p}$	$d_m = 36.7\, d_p = 1.16$ m (3.82 ft)	$a/g_o > 1.23 \times 10^{-5}$ g's Low Bo relationship may apply for some low acceleration uses.
	$\frac{d}{D} \frac{VO}{\dot{m}}\,_m = \frac{d}{D} \frac{VO}{\dot{m}}\,_p$	$d_m = 0.0176$ m (0.0579 ft)	$V_m d_m > 8.5 \times 10^{-4}$ m²/sec ($V_m d_m > 9.1 \times 10^{-3}$ ft²/sec)

FOLDOUT FRAME 2

For modeling based on maintaining similar flow and heat transfer regimes, the following limits were found for the jet velocity and orifice diameter of the jet:

Yuen and Chen, evaporating drops - $8.71 \times 10^{-4} < V_m d_m < 8.71 \times 10^{-3}$ m^2/sec

McGinnis, boiling drops - $V_m^2 d_m < 2.0$ m^3/sec^2

Selecting $d_m = d_p = 3.17$ mm (0.0104 ft) and a velocity of 2.29 m/sec (7.5 ft/sec) satisfies the regime constraints for both high and low Bond number mixing. The POTV will experience low Bond number mixing during high Earth orbit coasts and high Bond number mixing during propulsive maneuvers and the low Earth orbits.

Based on these requirements, inflow conditions were selected for the model so that the same flow and heat transfer regimes will be maintained in the model as in the prototype. The scaled receiver tank conditions are summarized in Table 2-XIV. The liquid requirement for line and tank childown was computed based on data presented in Reference 8 and assuming that the vent fluid leaving the tank exits at a temperature nearly equal to the average tank wall temperature.

TABLE 2-XIV SUMMARY OF CFMF MODEL CONDITIONS

	Model Receiver Tank	
Item	0.36 Scale	0.165 Scale
o Tank Configuration:		
Geometry	Cylindrical - 1.38 Elliptical Heads	Cylindrical - 1.38 Elliptical Heads
Volume	5.42 m^3 (191.3 ft^3)	0.52 m^3 (18.42 ft^3)
Diameter	1.52 m (4.98 ft)	0.69 m (2.28 ft)
Cylindrical Length	2.25 m (7.38 ft)	1.03 m (3.38 ft)
Total Length	3.35 m (10.98 ft)	1.53 m (5.03 ft)
Surface Area	16.7 m^2 (179.6 ft^2)	3.5 m^2 (37.8 ft^2)
Thickness	0.97 mm (0.038 in)	0.635 m (0.025 in)
Material	6061 Aluminum	6061 Aluminum
o Tank Weight:		
Dry Tank	45.8 Kg (101 lb)	7.26 Kg (16 lb)
Fluid Load (LH_2)	N/A	33.0 Kg (72.74 lb)
o Thermal/Fluid Parameters:		
Initial Temperature	300°K (540°R)	300°K (540°R)
Inlet Fluid (LH_2)	103 KPa (15 psia) Saturated	103 KPa (15 psia) Saturated
Fluid Velocity	2.71 m/sec (8.9 ft/sec)	2.29 m/sec (7.5 ft/sec)
Mass Flow Rate	22.7 gm/sec (0.05 lb/sec)	22.7 g[illegible]ec (0.05 lb/sec)
Prechill Temperature	114°K (205°R)	100°K (180°R)
Maximum Tank Pressure	241 KPa (35 psia)	241 KPa (35 psia)
Jet Diameter	15 Jets - 3.18 mm (0.125 in)	18 Jets - 3.18 mm (0.125 in)
Line and Tank Childown	2.9 Kg (6.4 lb)	0.95 Kg (2.1 lb)

2.7 Facility Hardware Description. The Phase I and Phase II facility general configurations are illustrated by Figures 2-17 and 2-18, respectively. The following paragraphs describe the major hardware components for both phases of the facility.

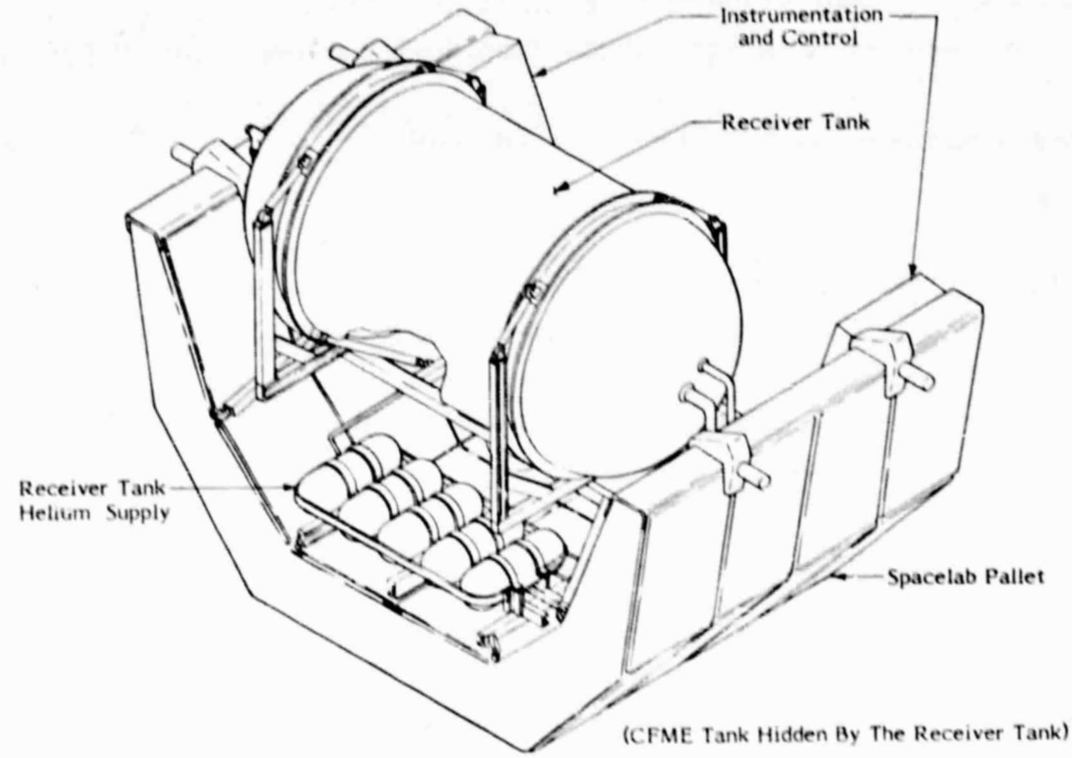


Figure 2-17 CFMF PHASE I SPACELAB PALLET

2.7.1 CFME Supply Tank. The CFME supply tank is a 0.60 m^3 (21.19 ft^3) spherical dewar. It has a TVS consisting of a vapor-cooled shield (VCS) and two heat exchangers. The primary heat exchanger operates in a steady state mode while the secondary heat exchanger operates in a transient mode.

2.7.2 Receiver Tanks. The Phase I receiver tank is to be a 0.36 scale POTV liquid hydrogen tank. It is a cylindrical tank having a total length of 3.35 m (10.98 ft), a diameter of 1.52 m (4.98 ft) and elliptical heads having a radius-to-height ratio of 1.38. The tank will be constructed of aluminum and will contain an inlet manifold, a helium diffuser and, to facilitate data acquisition, an instrumentation tree.

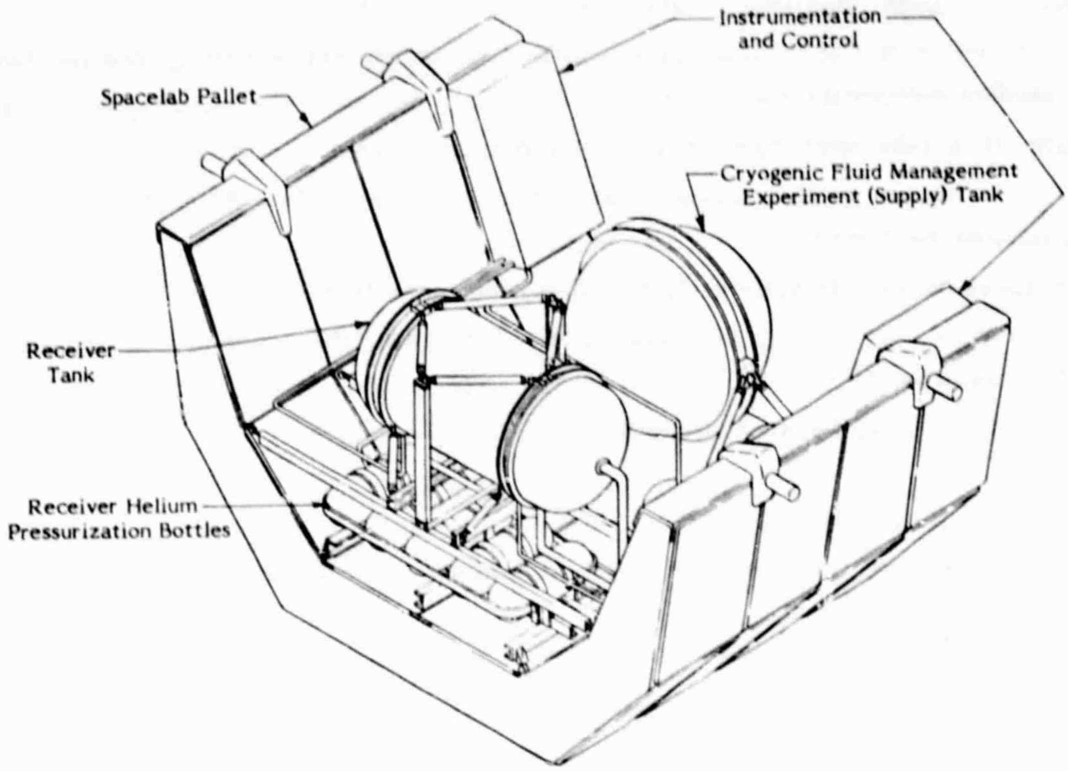


Figure 2-18 CFMF PHASE II PALLET

The Phase II receiver tank will represent a 0.165 scale POTV liquid hydrogen tank. It will also be an elliptically headed cylindrical tank with a radius-to-height ratio of 1.38 and a total length and diameter of 1.53 m (5.03 ft) and 0.85 m (2.78 ft), respectively. Unlike Phase I, the Phase II receiver tank will be used for two missions with different internal configurations for each mission. The Phase II, Mission Two, receiver tank will contain an inlet manifold, helium diffuser, instrumentation tree, tapered helium vent tube, vapor pullthrough suppression baffle and an internal Thermodynamic Vent System.

The Phase II, Mission Three, receiver tank will have an internal configuration similar to the Phase II, Mission Two, receiver tank with the replacement of the vapor pullthrough suppression baffle with a start basket. The following paragraphs describe the internal hardware of the receiver tank in more detail.

2.7.2.1 Inlet Manifold. The liquid inlet manifold's primary functions are to distribute liquid on the receiver tank wall and to assure mixing during receiver tank fill. Two possible techniques are available for accomplishing this: the use of spray nozzles and the use of a tube with holes placed longitudinally along it. Spray nozzles were the technique proposed in References 1 and 11 for use in the POTV. An analysis of the POTV spray nozzles to determine velocities at the nozzle exit and tank wall and the capability of the spray nozzles to satisfy fluid mixing requirements during fill of a POTV indicated that the spray nozzles may be inadequate. Therefore, the recommended approach for CFMF to assure sufficient mixing and heat transfer is the use of liquid jets provided by a tube with holes placed along its length.

2.7.2.2 Helium Diffuser. The purpose of the helium diffuser is to ensure that warm helium entering the receiver tank does not impinge directly on the capillary device or generate liquid spray.

2.7.2.3 Tapered Vent Tube. The function of the tapered vent tube is to shed liquid during venting, thereby allowing the venting of vapor only during low-g coast periods.

2.7.2.4 Liquid Acquisition Device. Liquid acquisition in the receiver tank during periods of low-g operation is accomplished by means of a start basket. The start basket is a screen device designed to trap liquid over the tank outlet during periods of low gravity. This trapped liquid serves as a vapor-free reservoir for boost pump and engine startup until the bulk of the liquid in the tank is settled and can be withdrawn from the tank outlet. The settled liquid refills the start basket for the next startup. A typical start basket configuration is illustrated by Figure 2-19.

There are a number of important considerations which determine the design of the start basket:

1. The quantity of liquid trapped in the start basket must be sufficient to provide outflow from the tank during settling and allow for evaporative losses from the screens during periods of low-gravity operation.

2. Liquid leaving the tank must be vapor free. This is usually accomplished by means of screened channels inside the start basket. These channels are designed so that they are in contact with liquid under all operating conditions. The wetted channel screens prevent vapor from entering the outlet.

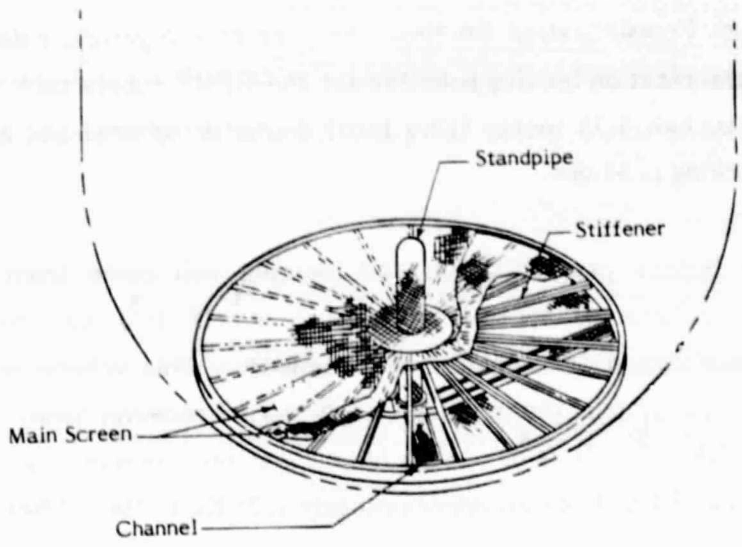


Figure 2-19 GENERAL START BASKET CONFIGURATION

3. The screens forming the surface of the start basket must be sized to retain liquid at all expected acceleration levels.

4. The screen geometry of the start basket must provide rapid wicking of liquid along the screen to replace evaporative losses and prevent screen dry-out during low-gravity operation.

5. The overall geometry of the start basket must be designed to permit rapid refilling at expected tank liquid levels.

2.7.2.5 Vapor Pullthrough Suppression. The Phase II, Mission Two, receiver tank may contain a vapor pullthrough suppression baffle to prevent the ingestion of vapor into the outflow line during receiver tank depletion. The receiver tank will be drained by utilizing the RCS primary thrusters to settle the liquid in the tank. Without the baffle, vapor ingestion may occur for the low-g levels generated by the RCS primary thrusters resulting in excessive liquid residuals.

2.7.3 Helium Pressurization Bottles. As part of the ground rules for this study, the four helium pressurization bottles selected for the CFME supply tank were to be used. These tanks are titanium 0.35 meter (13.9 inch) diameter spheres and are rated at 22.1 MPa (3200 psia) working pressure.

The receiver tank helium pressurization and inerting will come from an independent source. A helium volume of approximately 0.23 m^3 (8 ft^3) was determined to be sufficient for pressurization and inerting requirements. This volume was based on the worst case helium requirement: the inerting of the Phase I receiver tank. This tank has an internal volume of 5.4 m^3 (191 ft^3). Assuming a final tank temperature and pressure of 280°K (504°R) and 241 KPa (35 psia), approximately 2.27 Kg (5 lbs) of helium are required for a single tank pressurization. The inerting of the tank will consist of one charge, blowdown and a final charge. Therefore, approximately 4.54 Kg (10 lbs) of helium is required to complete receiver tank inerting. A factor of safety of 1.5 was used to ensure that sufficient helium will exist for any unforeseen events. The requirement for 0.23 m^3 (8 ft^3) of stored helium was determined using a helium loading temperature of 300°K (540°R) and a working pressure of 20.7 MPa (3000 psia).

2.7.4 Data Acquisition and Control and Data Recording. The Data Acquisition and Control System (DACS) is a microprocessor based computer used to monitor and control the experiment. This study was directed to examine the applicability of the DACS and tape recording equipment used in the CFME design study for the entire facility.

2.7.5 Instrumentation. Instrumentation requirements to determine that the facility is functioning properly, control the experiment and collect data on the performance of the facility were identified. These requirements are: (1) temperature measurements, (2) pressure measurement, (3) liquid vapor sensing, (4) quality measurement and (5) mass gauging.

3.0 FACILITY CONCEPTUAL DESIGN AND ANALYSIS

This section describes the conceptual design and analysis of the Cryogenic Fluid Management Facility (CFMF) based on the preliminary facility definition contained in Section 2.0. The conceptual design includes a description of the receiver tanks, support structure, acquisition device, thermal and pressure control systems required for the supply and receiver tanks, all fluid fill, drain, vent and transfer lines, instrumentation, data acquisition and experiment control systems. Structural, thermal, fluid mechanic and safety/reliability analyses were conducted based on the conceptual design. In addition, Payload Specialist involvement and ground support equipment requirements are identified. An experimental test plan was developed for each mission, including ground test requirements, launch procedures and on-orbit operations.

3.1 Facility Conceptual Design. This paragraph describes the CFMF hardware requirements for both phases, including the drawings produced for each phase. Table 3-I contains a list of the drawings by figure number. In some cases, the Phase I and II drawings are identical. These drawings will only be included in the Phase I design.

TABLE 3-I CFMF DRAWING LIST

Drawing Title	Figure Number
General Arrangement, Phase I	3-1
Flow Schematic, Phase I	3-2
Receiver Tank, Phase I	3-3
Receiver Tank Insulation, Phase I	3-4
Insulation Attachment	3-5
Insulation Lap Joint	3-6
Strut Detail	3-7
Helium Pressurization Bottles	3-8
Component Details	3-9
Instrumentation Tree, Phase I	3-10
Instrumentation Pallet A, Phase I	3-11
Instrumentation Pallet B, Phase I	3-12
General Arrangement, Phase II	3-13
Flow Schematic, Phase II	3-14
Receiver Tank, Phase II, Mission Two	3-15
Receiver Tank, Phase II	3-16
Receiver Tank Insulation, Phase II	3-17
Instrumentation Tree, Phase II	3-23
Instrumentation Pallet A, Phase II	3-24
Instrumentation Pallet B, Phase II	3-25

3.1.1 Phase I Design. The Phase I facility general arrangement is shown in Figure 3-1. The major hardware components are the receiver tank, supply tank, helium pressurization system and supporting hardware. The following subparagraphs describe the flow schematic and hardware components.

3.1.1.1 Flow Schematic. The flow schematic was developed to be consistent with the Phase I experimental objectives. This flow schematic and a description of the function of each of its components are given in Figure 3-2 and Table 3-II. The data and control columns in Table 3-II differentiate which instruments collect data and which instruments control the experiment. A safety consideration in the development of the facility was to assure that no single component failure would endanger the Space Shuttle. This approach mandated that critical active components, such as valves, be protected by a passive system using a burst disc or relief valve.

The first objective of the Phase I facility is the evaluation of the supply tank liquid acquisition device's capability to provide vapor-free liquid outflow. This will be accomplished by measuring outflow quality from the acquisition device with quality meter QM2. QM2 will be calibrated by independently determining the average outflow quality and volumetric flow. The average outflow quality is evaluated by measuring the power required for heater HX1 to vaporize and slightly superheat the outlet fluid. At a given heater power of 2080 watts, the maximum mass flow for which quality verification is possible is directly proportional to quality. For an outflow quality of 0.0, verification of the quality is possible only for mass flow rates less than 1.35 g/sec (0.003 lb/sec). For higher flow rates, either a larger heater would be required or it must be demonstrated that the accuracy of the quality meter is independent of mass flow rate. The volumetric flow rate is measured by volumetric flow meter VM1. To assure that condensation does not occur within VM1, additional heat may be added to the flow through HX2.

The second objective of Phase I is demonstration of the on-orbit quantity gauging system for the supply tank. The method proposed for calibrating the mass gauging system is based on knowing the initial quantity of liquid hydrogen in the supply tank at launch and keeping track of all exiting flows. The proposed quality meters, QM1 and QM2, have a built-in integrating capability which will allow for the summation of outflows.

The third and fourth objectives are evaluation of the transfer line and receiver tank cooldown processes. Receiver tank prechill and chill will involve the charge, hold and vent procedure outlined in Paragraph 2.2. The prechill charge is initiated by opening flow

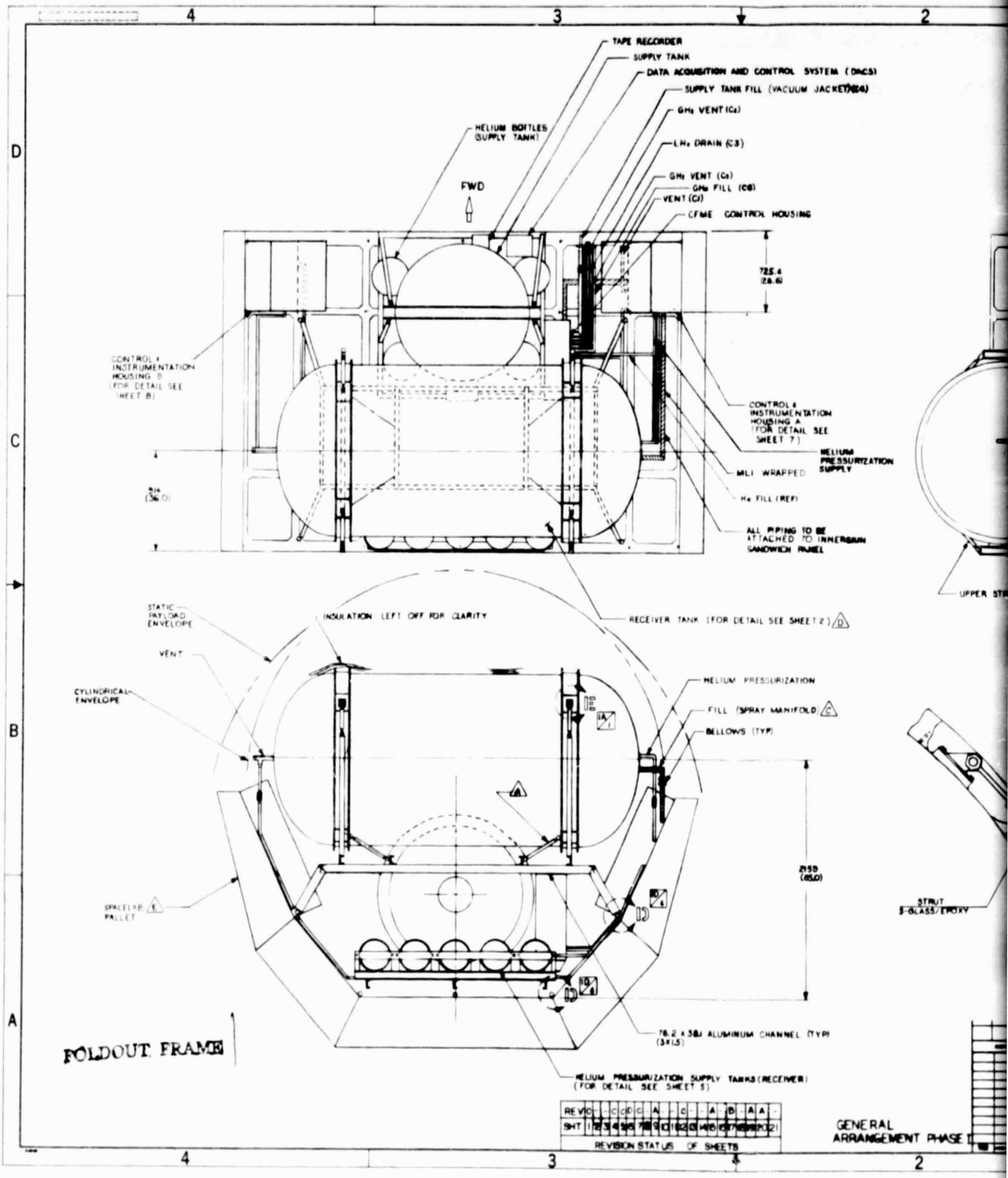
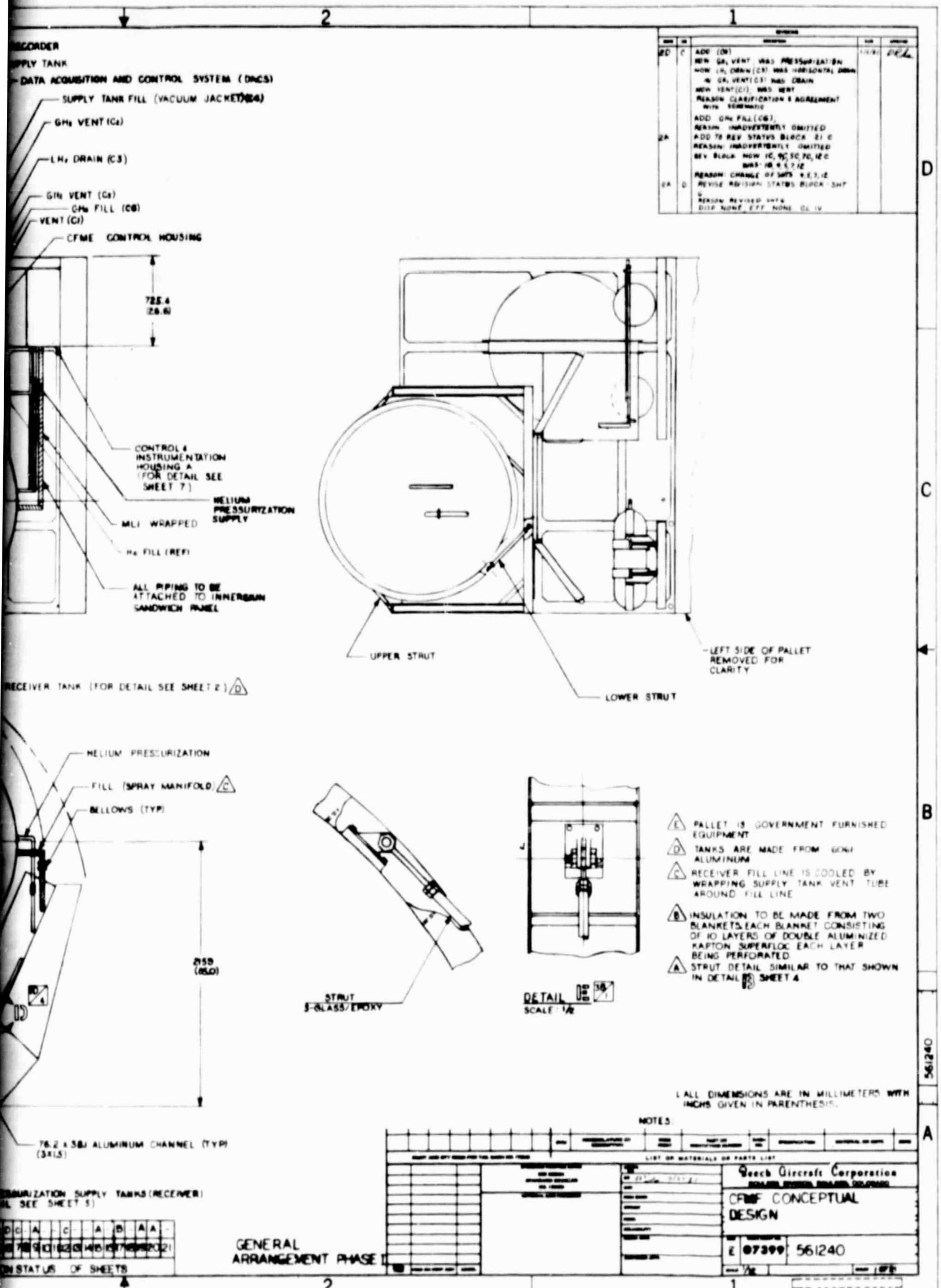


Figure 3-1 PHASE I FACILITY GENERAL ARRANGEMENT



FOLDOUT FRAME

SE I FACILITY GENERAL ARRANGEMENT

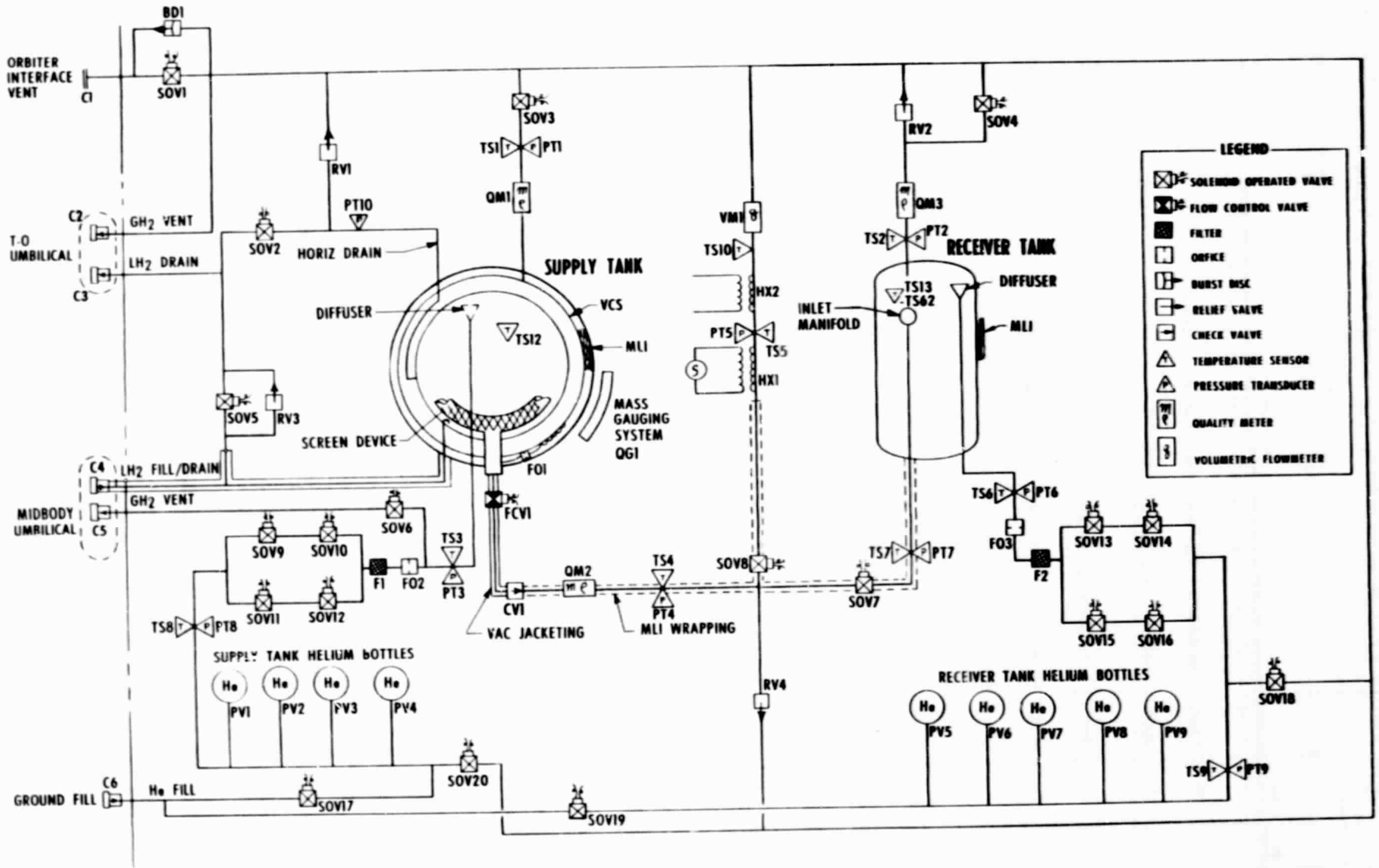


Figure 3-2 PHASE I FACILITY FLOW SCHEMATIC

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TABLE 3-II PHASE I FLOW SCHEMATIC COMPONENT FUNCTION

Component Identification Number	Data	Control	Function
SOV1		X	Opens upon orbit insertion to permit venting; closed during ground operations to allow venting through T-0 umbilical.
SOV2		X	Opens during horizontal drain operations; activated only when supply tank is loaded upon landing.
SOV3		X	Opens to permit operation of supply tank TVS.
SOV4		X	Allows receiver tank venting.
SOV5		X	Opens to permit supply tank ground drain at time < 4 hours by utilizing T-0 umbilical; closed during flight operation and ground fill.
SOV6		X	Open during supply tank fill; allows GH_2 venting during fill; closed during all other operations.
SOV7		X	Opens to allow LH_2 to enter receiver tank through inlet manifold; may be opened during emergency conditions resulting from receiver tank overpressurization.
SOV8		X	Opens during calibration of QM2; may be opened if receiver tank overpressurizes to provide additional venting capability.
SOV9		X	First valve in supply tank primary pressurization system; operates only when SOV10 is closed.
SOV10		X	Second valve in supply tank primary pressurization system; operates only when SOV9 is closed.
SOV11		X	First valve in supply tank backup pressurization system; operates only when SOV 12 is closed.
SOV12		X	Second valve in supply tank backup pressurization system; operates only when SOV11 is closed.
SOV13		X	Second valve in receiver tank primary pressurization system; operates only when SOV14 is closed.
SOV14		X	First valve in receiver tank primary pressurization system; operates only when SOV13 is closed.
SOV15		X	Second valve in receiver tank backup pressurization system; operates only when SOV16 is closed.
SOV16		X	First valve in receiver tank backup pressurization system; operates only when SOV15 is closed.
SOV17		X	Opens during supply tank helium bottle pressurization performed in KSC Operations and Control (O&C) Building.
SOV18		X	Allows venting of receiver tank helium bottles if an overpressurization condition is detected by PT9.
SOV19		X	Open during receiver tank helium bottle pressurization performed in KSC O&C Building.
SOV20		X	Permits venting of supply tank helium bottles if an overpressurization condition is detected by PT8.
FCV1			Controls supply tank outflow rate; opens during calibration of QM2, evaluation of supply tank capillary device and during receiver tank prechill.
RV1			Prevents overpressurization of supply tank during all operations.
RV2			Protects receiver tank from overpressurization during all operations.
RV3			Protects supply tank from overpressurization during ground loading operations.
RV4			Protects transfer line components from overpressurization resulting from LH_2 boiling in closed line segment between FCV1, SOV8 and SOV7.
BD1			Protects entire facility upon failure of SOV1; low pressure burst disk bursts at approximately 103 kPa (15 psid).
PT1	X		Supply tank TVS exiting pressure.
PT2	X	X	Receiver tank vent pressure and tank pressure.
PT3	X		Supply Tank pressurization line pressure.
PT4	X		Transfer line pressure at supply tank outlet.
PT5	X	X	Heat exchanger (HX1) pressure used to determine saturation temperature which controls heater input.
PT6	X		Receiver tank pressurization line pressure.

TABLE 3-II PHASE I FLOW SCHEMATIC COMPONENT FUNCTION (Concluded)

Component Identification Number	Data	Control	Function
PT7	X		Transfer line pressure at receiver tank inlet.
PT8		X	Supply tank helium pressurization supply pressure.
PT9		X	Receiver tank helium pressurization supply pressure.
PT10	X	X	Supply tank pressure.
TS1	X		Supply tank TVS exit temperature.
TS2	X		Receiver tank vent temperature.
TS3	X		Supply tank pressurization line temperature.
TS4	X		Transfer line temperature at supply tank outlet.
TS5		X	Heat exchanger (HX1) exit temperature; given PT5, this temperature is controlled to slightly greater than the corresponding saturation temperature.
TS6	X		Receiver tank pressurization line temperature.
TS7	X		Transfer line temperature at receiver tank inlet.
TS8		X	Supply tank helium pressurization supply temperature; used with PT8 and helium bottle volumes to determine helium quantity.
TS9		X	Receiver tank helium pressurization supply temperature used with PT9 and helium bottle volumes to determine helium quantity.
TS10		X	Exit temperature to heat exchanger (HX2) used to ensure that volumetric flow meter (VM1) measures vapor flow by controlling heat input.
QM1	X		Supply tank TVS exit flow quality and flow rate.
QM2	X	X	Supply tank outflow quality used to determine supply tank capillary device performance.
QM3	X		Receiver tank vent quality used to determine if liquid is vented.
VM1	X		Determines volumetric flow rate; used with quality determined from heat exchanger (HX1) to calibrate QM2.
FO1			Visco-jet used to provide isenthalpic expansion of supply tank TVS flow.
FO2			Restricts supply tank helium pressurant flow rate.
FO3			Restricts receiver tank helium pressurant flow rate.
F1			Filter used to prevent clogging of FO2.
F2			Filter used to prevent clogging of FO3.
QG1	X	X	Supply tank quantity measurement.
HX1			Heat exchanger for calibration of QM2.
HX2			Heat exchanger to insure vapor flow through VM1.

control valve FCV1 and solenoid operated valve SOV7; SOV4 will be open during prechill vent. Transfer line cooldown will be completed during the initial prechill charge cycles. Temperature sensors along the transfer line and within the receiver tank will be used to collect the cooldown data.

In addition to meeting the experiment objectives, the flow network must permit performance of certain other tasks, for example, the helium pressurization and inerting of the supply and receiver tanks.

3.1.1.2 Supply Tank. The supply tank is the CFME tank described in Reference 36. A brief description of the supply tank support structure, thermal and pressure control systems follows.

Support Structure. Figure 2-18 shows the supply tank mounted on the Spacelab pallet. The pressure vessel is supported within the outer shell by two S-glass/epoxy trunnions attached to the girth ring. The girth ring is positioned in the Y-Z plane (reference Figure 2-2) when mounted in the Spacelab pallet and attaches to the base support frame through two bipod struts and a shear support.

Thermal Control System. The thermal control system consists of a vacuum jacket, Thermodynamic Vent System (TVS) and Multilayer Insulation (MLI). The vacuum jacket provides an evacuated annulus around the pressure vessel and protection for the MLI. The TVS maintains tank pressure by venting hydrogen from the liquid acquisition device through two heat exchangers, each having an orifice to reduce hydrogen pressure and temperature. These heat exchangers intercept heat at the tank penetrations and through the MLI. Flow in the two heat exchangers is controlled by on-off latching solenoid valves actuated by the Data Acquisition and Control System (DACS). The MLI consists of 75 layers of double aluminized mylar between the vapor-cooled shield and the outer shell.

Pressurization Control System. The pressurization control system described in Reference 36 is shown schematically in Figure 3-2. It consists of two pairs of solenoid operated valves separated by a preset length of line. Helium is injected into the supply tank by a series of two solenoid operated valves. The valve closest to the helium supply is opened and the pressure in the section of line between the two valves equalizes at the helium supply pressure. This valve is then closed and the valve closest to the supply tank is opened allowing the trapped quantity of helium to enter the supply tank. This valve is then closed and the sequence is repeated as required.

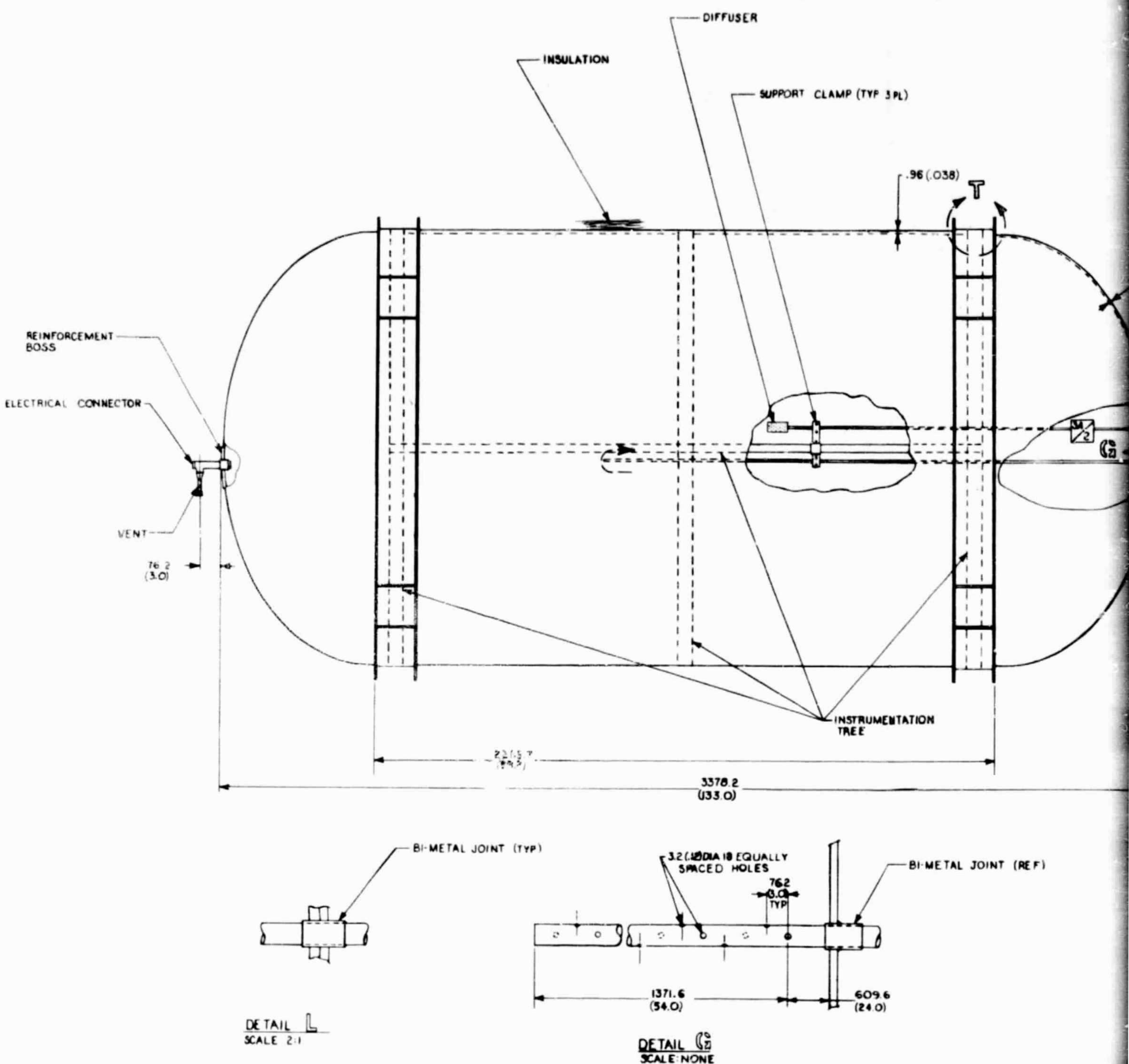

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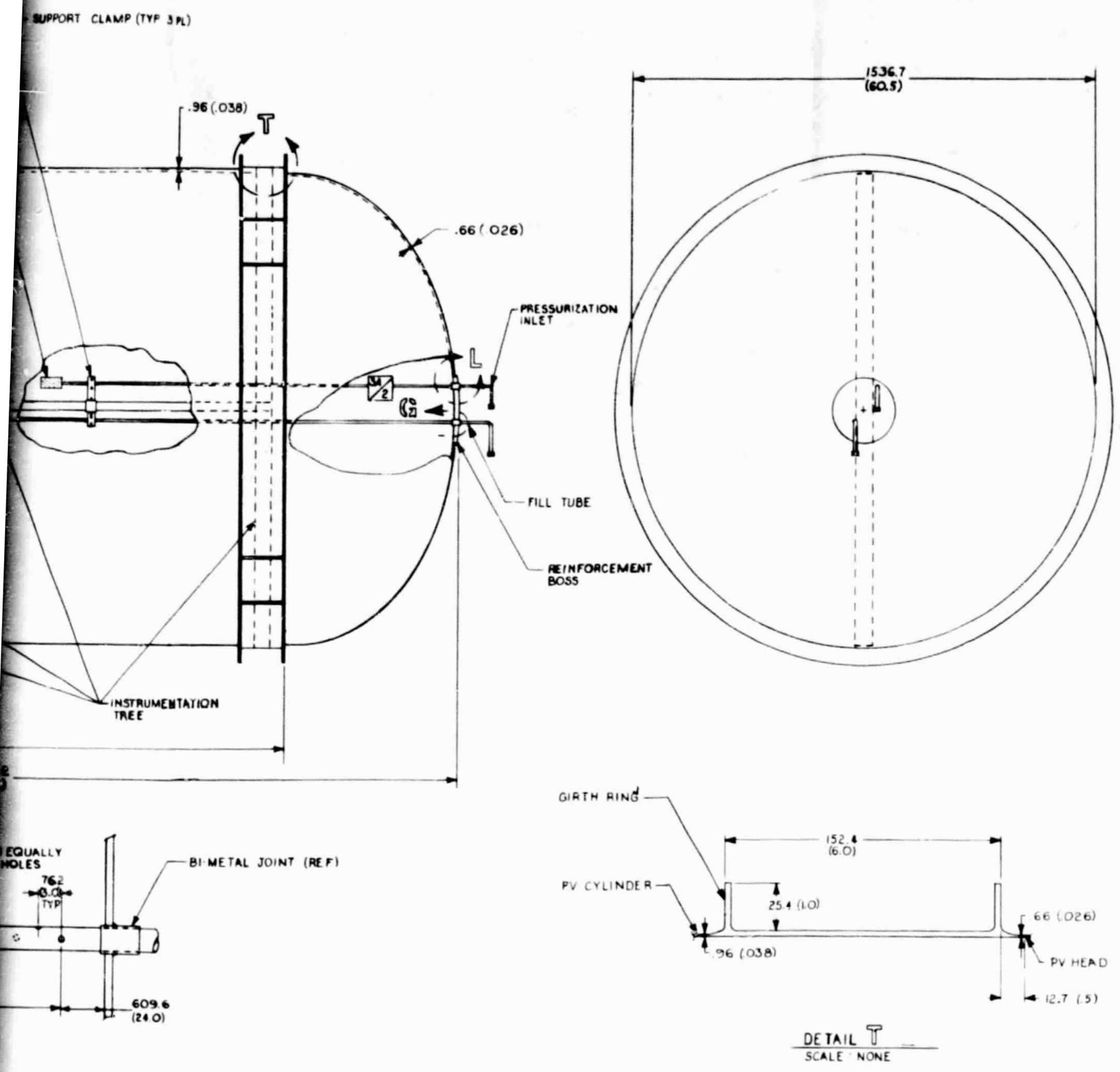
Figure 3-3 PHASE I RECEIVER TANK CONFIGU



PHASE I RECEIVER TANK CONFIGURATION

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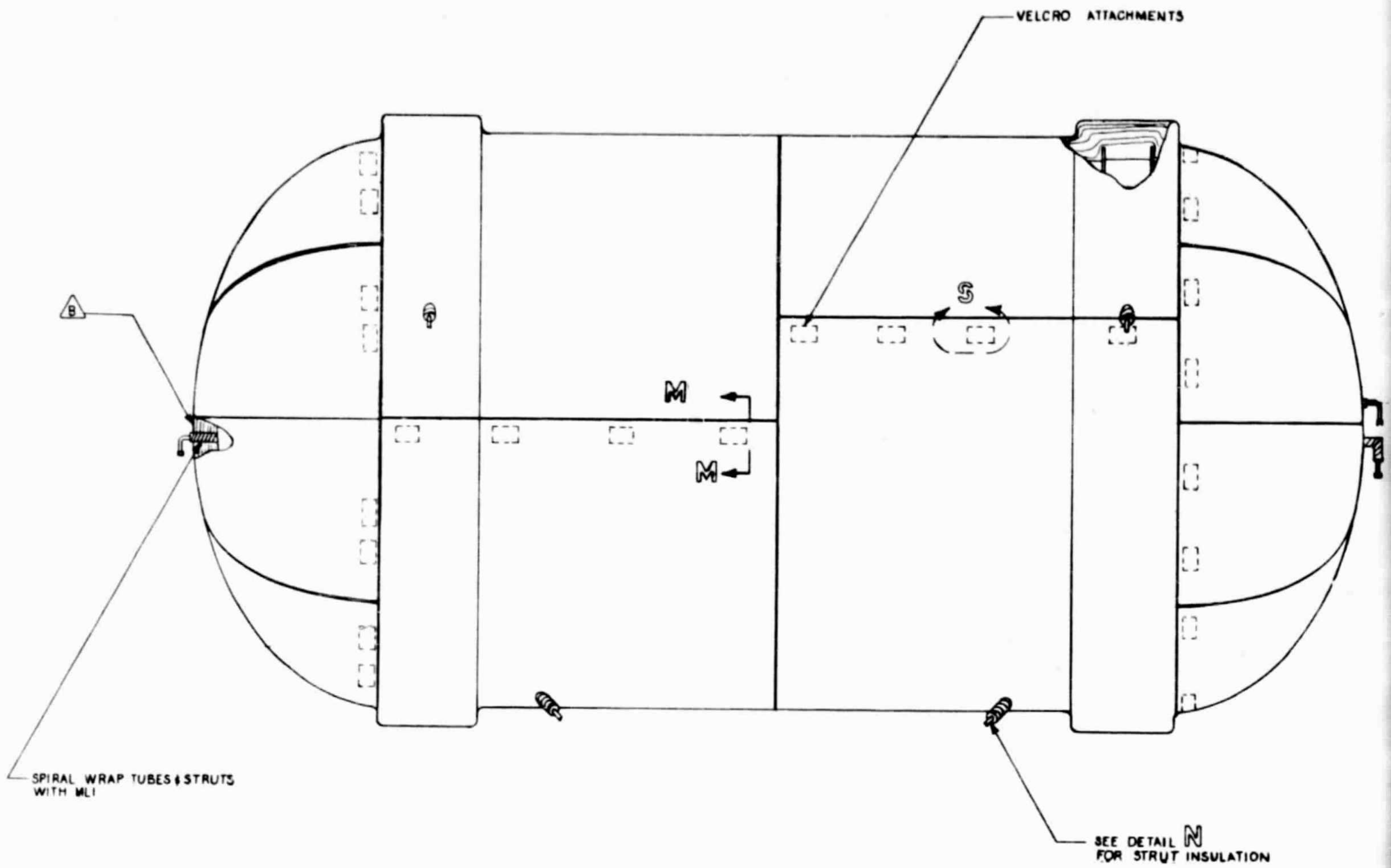

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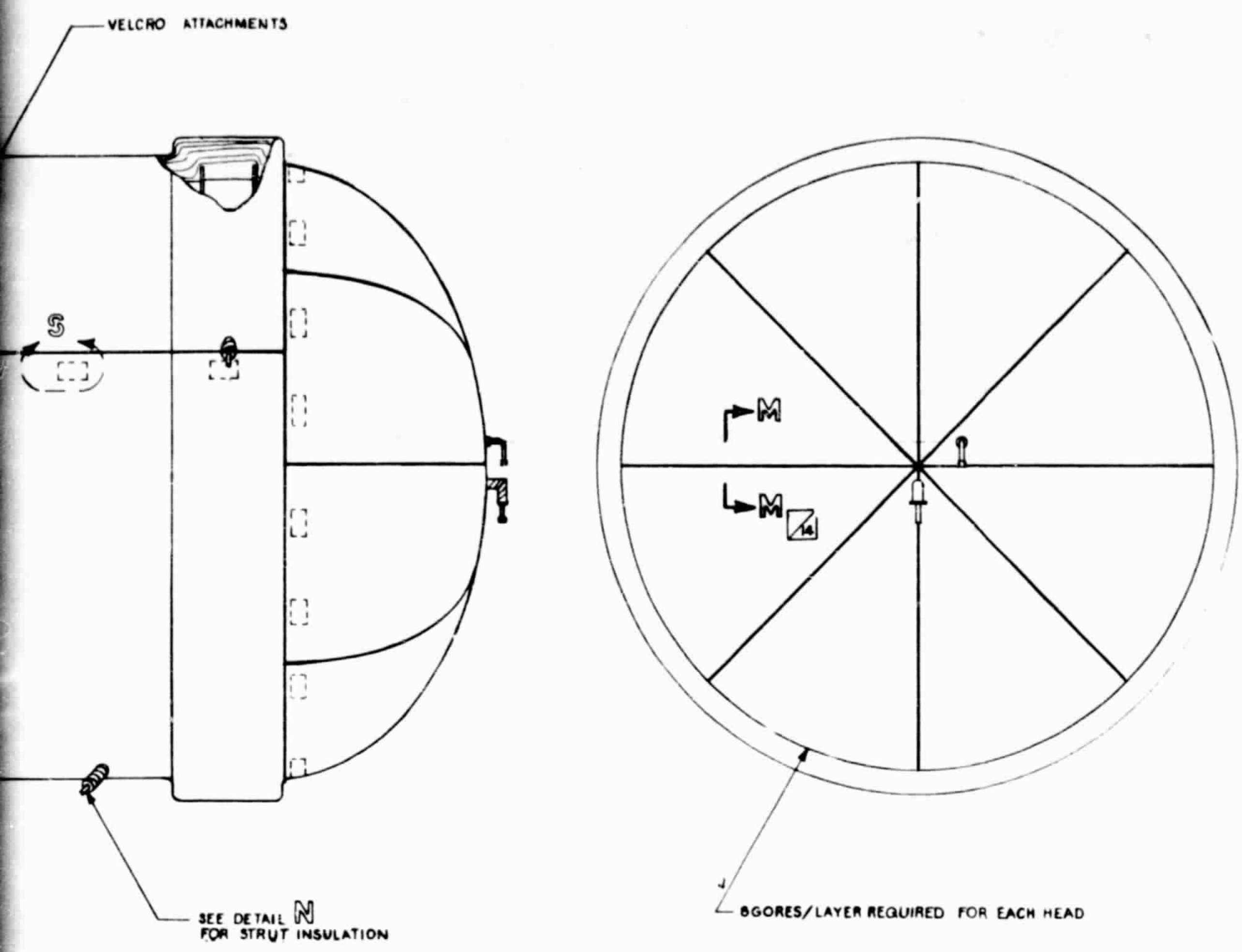
Figure 3-4 PHASE I RECEIVER TANK INSULAT



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63

3-4 PHASE I RECEIVER TANK INSULATION

3.1.1.3 Receiver Tank. The receiver tank for Phase I is a 0.36 scale POTV liquid hydrogen tank containing an inlet manifold, instrumentation tree, helium diffuser and vent device. Figure 3-3 shows the receiver tank and its internal configuration. The following paragraphs describe the subsystems which make up this receiver tank.

Thermal Protection System. The thermal protection system for the 0.36 scale receiver tank consists of 20 layers of double-aluminized Kapton Superfloc and 8 S-glass/epoxy struts. The selection of Superfloc as the insulation material for the CFMF was based on the insulation system currently being developed by Marshall Space Flight Center (MSFC) for a full-scale POTV. The receiver tank insulation layup, Figure 3-4, shows that eight gore sections per head and two cylindrical sections are required. Figure 3-5 shows the attachment method to be used for the MLI installation. The attachment technique utilizes two velcro halves. The half attached to the pressure vessel is larger than the half attached to the insulation to allow for alignment during installation. A typical insulation lap joint is shown in Figure 3-6. Two 10-layer blankets are overlapped by a minimum of 50 mm (2 in) and fastened together by thread attached to two nylon buttons. To allow evacuation of the MLI during on-orbit operation, the insulation and the face sheet are perforated. The tank is thermally isolated from its surroundings by the eight S-glass/epoxy struts.

Support System. The receiver tank is mounted to the Spacelab pallet via an aluminum support system which attaches to the pallet hardpoints. The tank is supported from this structure by eight S-glass/epoxy struts, shown in Figure 3-7.

Pressure Control System. The Phase I receiver tank will not contain liquid and therefore will not require helium for liquid expulsion; however, helium is required for tank inerting. The receiver tank pressurization system is identical to the supply tank pressurization system and operates in a similar manner. The helium supply for the receiver tank consists of five Kevlar-wound aluminum lined cylindrical high-pressure bottles. They have a volume of 26.7 liters (1631 in^3) each and a maximum design pressure of 21 MPa (3000 psi). The bottles are mounted to a subpallet to facilitate handling and assembly during Spacelab pallet integration (Figure 3-8). These bottles are currently undergoing Shuttle qualification for the Manned Maneuvering Unit (MMU).

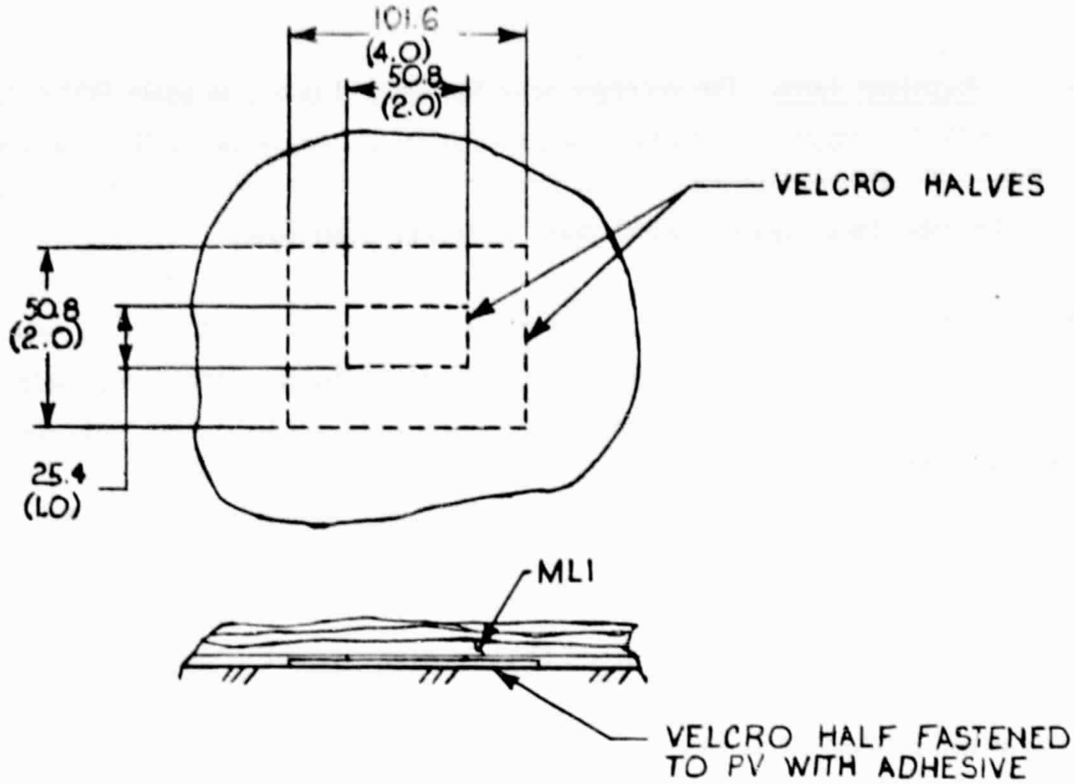


Figure 3-5 INSULATION ATTACHMENT

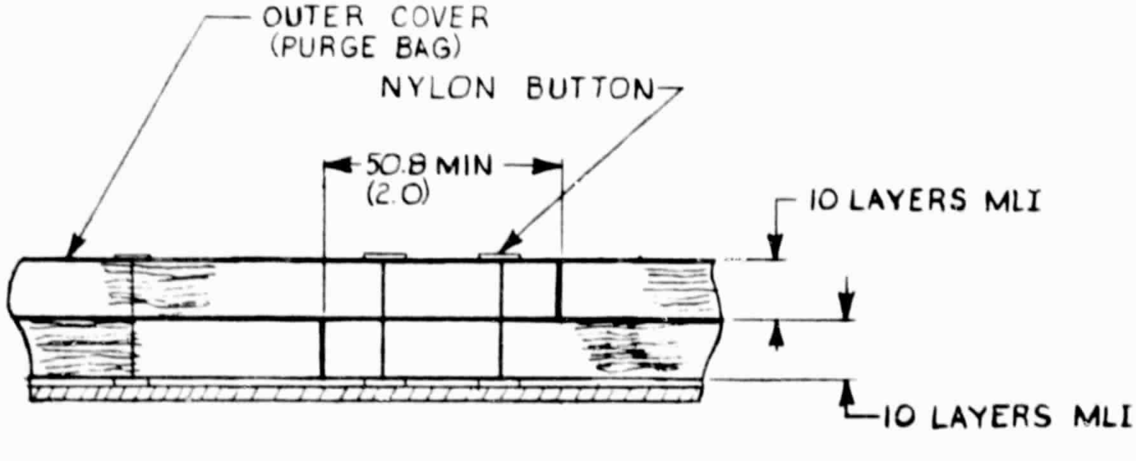
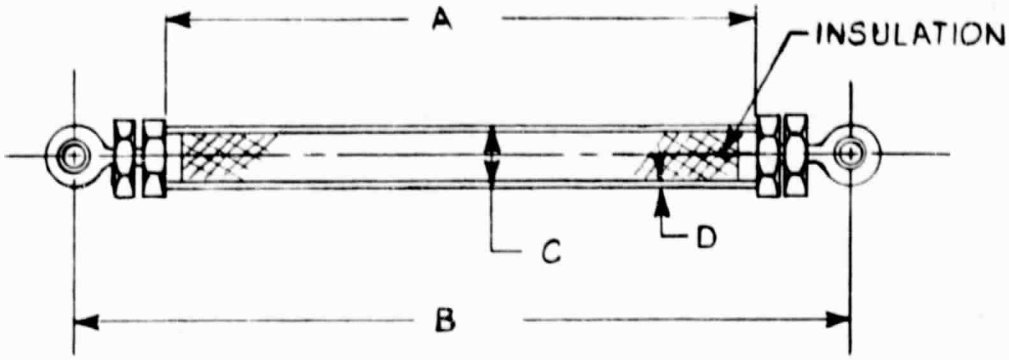


Figure 3-6 INSULATION LAP JOINT



		A	B	C	D
PHASE I	UPPER	381.0 (15.0)	457.2 (18.0)	38.1 (1.5)	0.66 (0.026)
	LOWER	444.5 (17.5)	520.7 (20.5)	31.0 (1.22)	0.66 (0.026)
PHASE II	UPPER	533.4 (21.0)	609.6 (24.0)	23.4 (0.92)	0.66 (0.026)
	LOWER	228.6 (9.0)	304.8 (12.0)	10.7 (0.42)	0.66 (0.026)

Figure 3-7 SUPPORT STRUT DETAIL

Inlet Manifold. The function of the inlet manifold is to distribute liquid uniformly onto the tank wall and provide jet velocities sufficient to ensure mixing during fill. The inlet manifold consists of a 1.38 m (54 in) straight section of tube. This tube is perforated by 15 holes along its axial length. An analysis (Paragraph 3.2) of the pressure drop was conducted to determine the inlet manifold diameter and length required to provide uniform flow from each hole.

Helium Diffuser. Although the Phase I receiver tank will contain only vapor, the helium diffuser was designed to prevent liquid hydrogen spray caused by helium pressurant impingement upon the liquid surface during pressurization. The critical Weber number stability criteria contained in Reference 37 is given in Equation 3-1:

$$We_{crit} = Re^{.8}/89 \qquad \text{(Equation 3-1)}$$

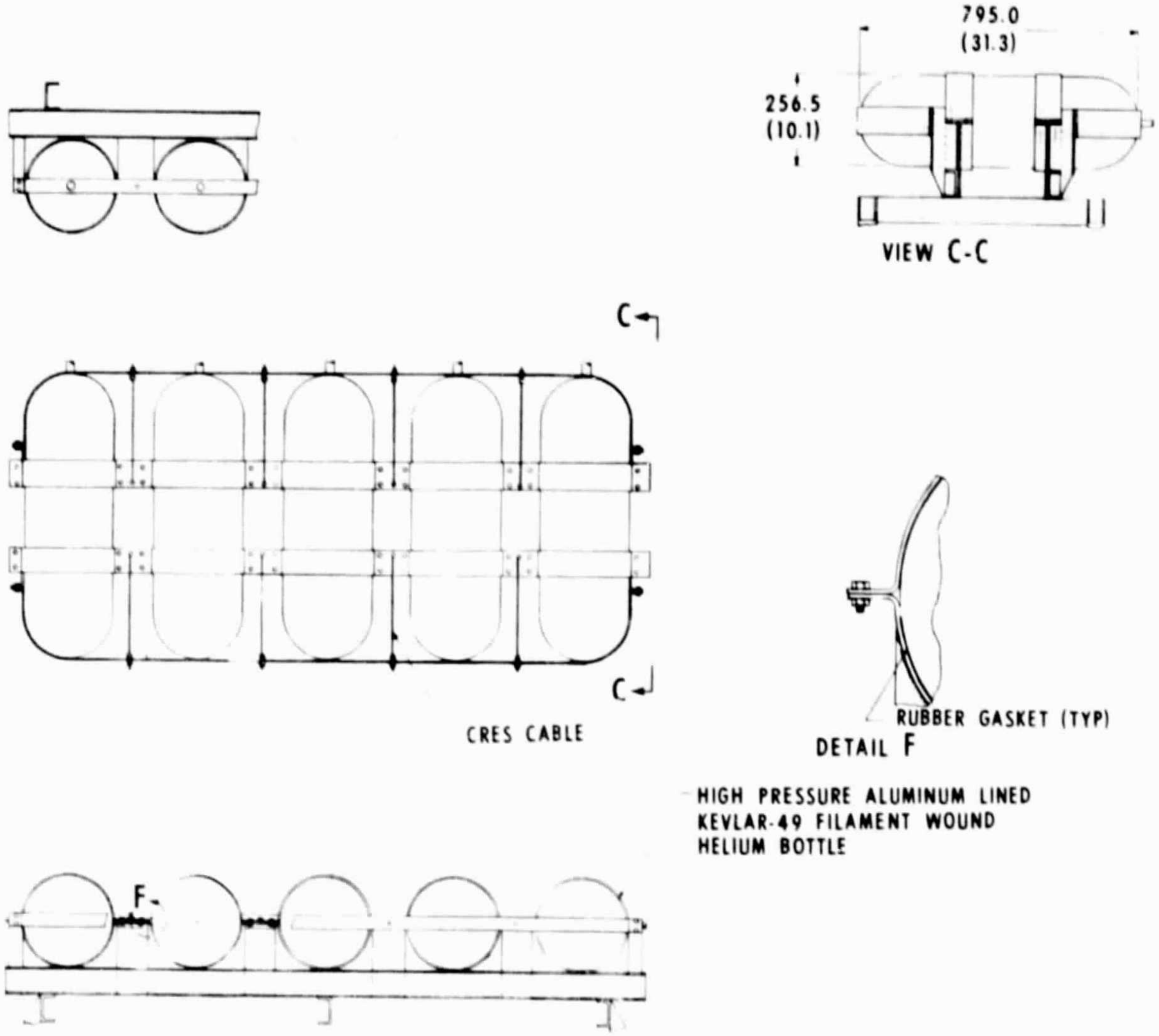
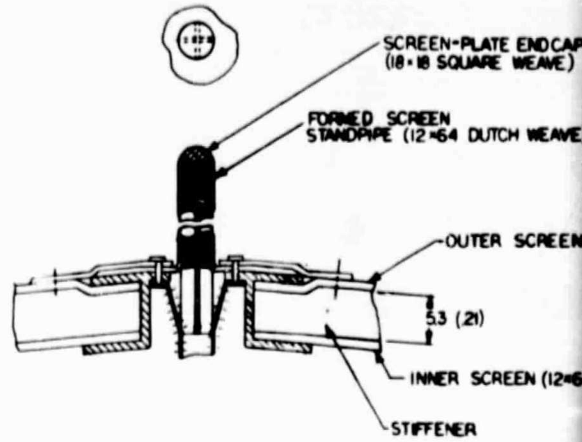
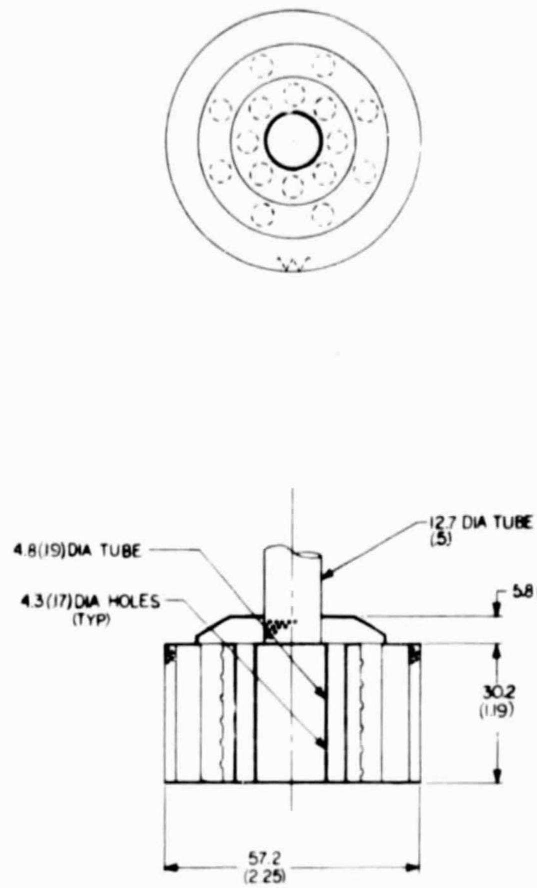


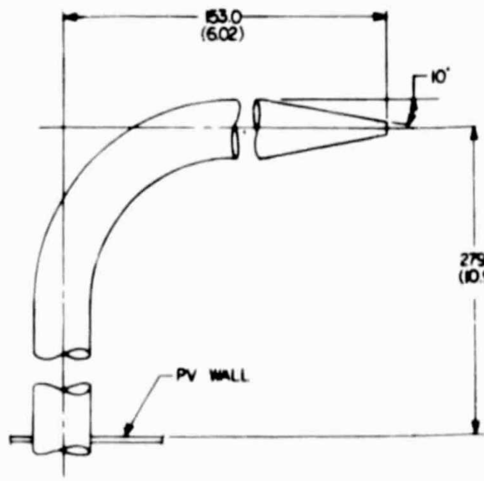
Figure 3-8 CFMF RECEIVER TANK
HELIUM PRESSURIZATION SUPPLY BOTTLES



VIEW U
SCALE: NONE



DIFFUSER (PHASE I & II)
SCALE: 2/1



VENT TUBE DETAIL (PHASE II)
SCALE: 2/1

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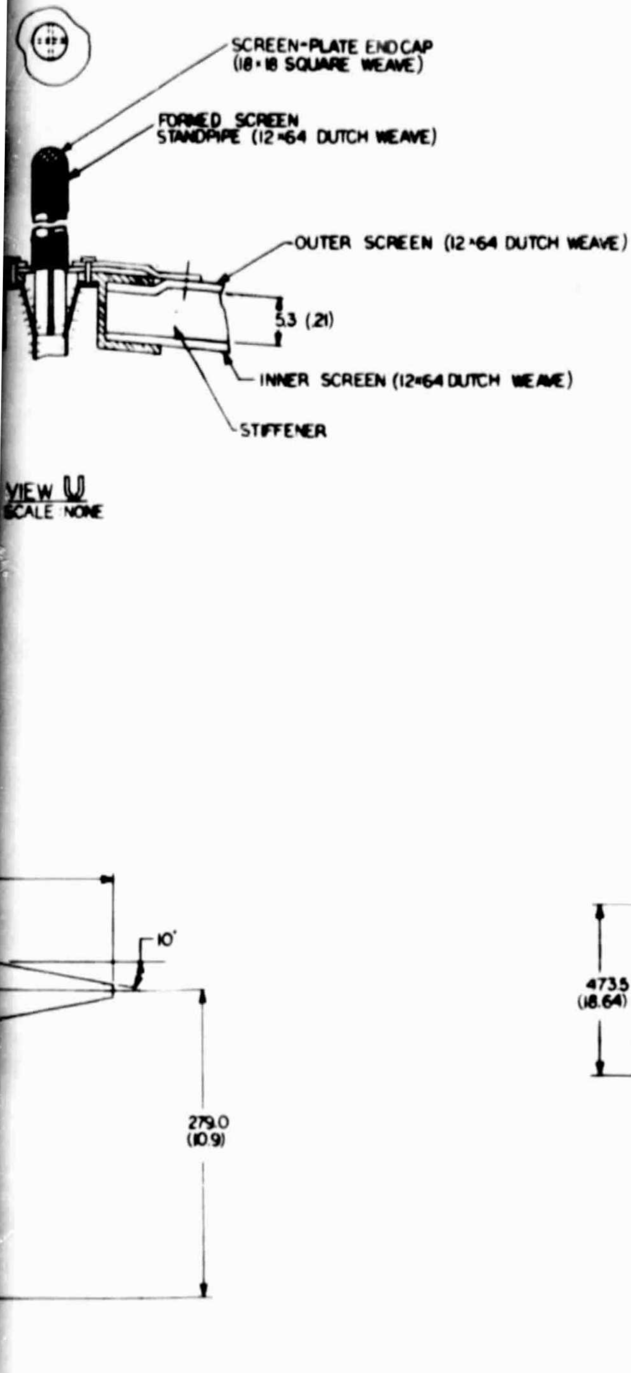
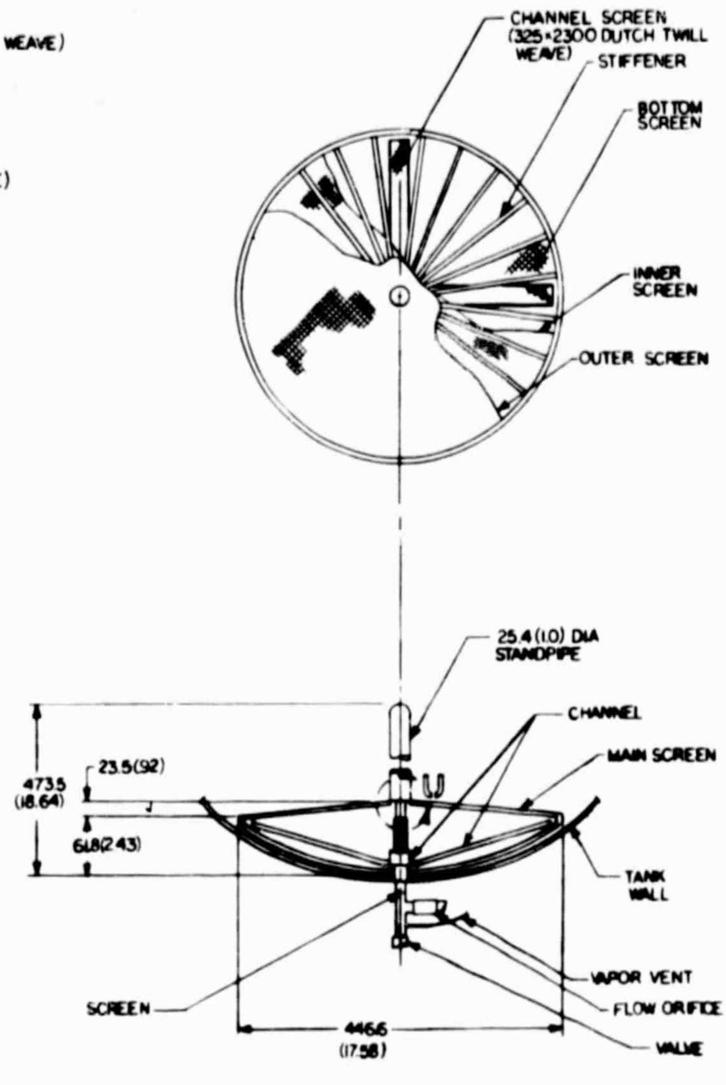
Figure 3-9 CFMF RECEIVER TANK COMPO



DETAIL (PHASE II)
SCALE 2/1



START BASKET (PHASE II)
SCALE: NONE

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CFMF RECEIVER TANK COMPONENT DETAILS

where:

$$We_{crit} = \frac{\rho_g \bar{V}_j^2 d_o}{\sigma g_c}$$

$$Re = \rho_g \bar{V}_j d_o / \mu_g$$

$$\bar{V}_j = \frac{4 \dot{m}}{\rho d_o^2}$$

ρ_g = Ullage density

$\bar{V}_j$ = Inlet velocity

d_o = Characteristic dimension

μ_g = Ullage viscosity

$\dot{m}$ = Pressurant flow rate

g_c = Gravitational constant

σ = Surface tension

Using a maximum pressurant inlet flow rate of 9 kg/hr (20 lbs/hr), the velocity $\overline{V_j}$ must be less than 1.8 m/sec (6 ft/sec) and, therefore, d_o must be greater than 47.0 mm (1.85 in) for the cavity stability criterion of Reference 37 to be satisfied. This criterion must be met to prevent liquid spray from forming during pressurization. The design of the helium diffuser, shown in Figure 3-9, was based on the design contained in Reference 38 and scaled to the CFMF application. This design will adequately attenuate velocities to below 1.8 m/sec (6 ft/sec) for all CFMF conditions, provided the helium inlet flow rate is less than 9 Kg/hr (20 lb/hr).

Instrumentation Tree. The receiver tank contains an instrumentation tree constructed of S-glass/epoxy to minimize thermal mass (Figure 3-10). This tree is contained within the tank, as shown in Figure 3-3, and is used to mount instrumentation to provide information on tank fluid temperature. During final design of the instrumentation tree, its effect on the liquid behavior during low-g and settling will have to be assessed.

3.1.1.4 Instrumentation and Control Pallets. Two subpallets are used in the Phase I design to provide mounting for instrumentation and valving. Figures 3-11 and 3-12 show the component layouts on pallets A and B; their locations on the Spacelab pallet are shown in Figure 3-1.

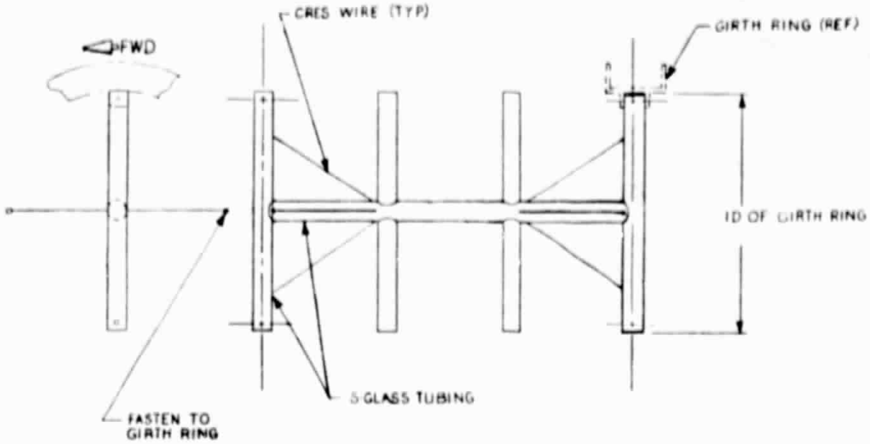


Figure 3-10 PHASE I RECEIVER TANK INSTRUMENTATION TREE

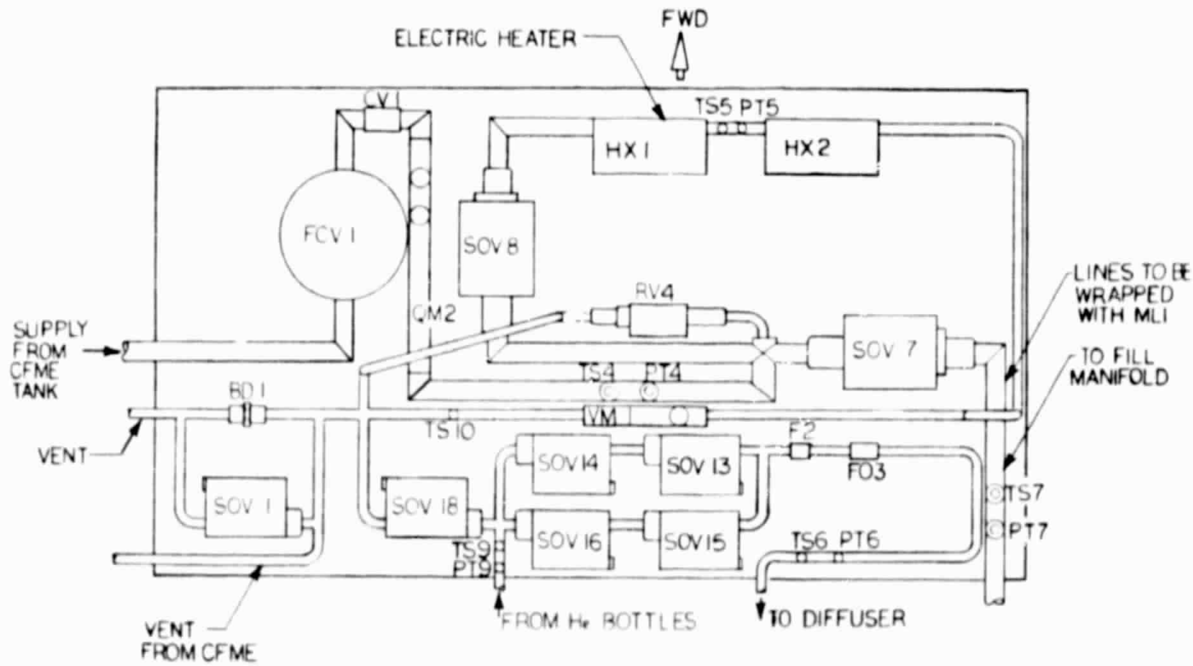


Figure 3-11 PHASE I INSTRUMENTATION AND CONTROL PALLET A

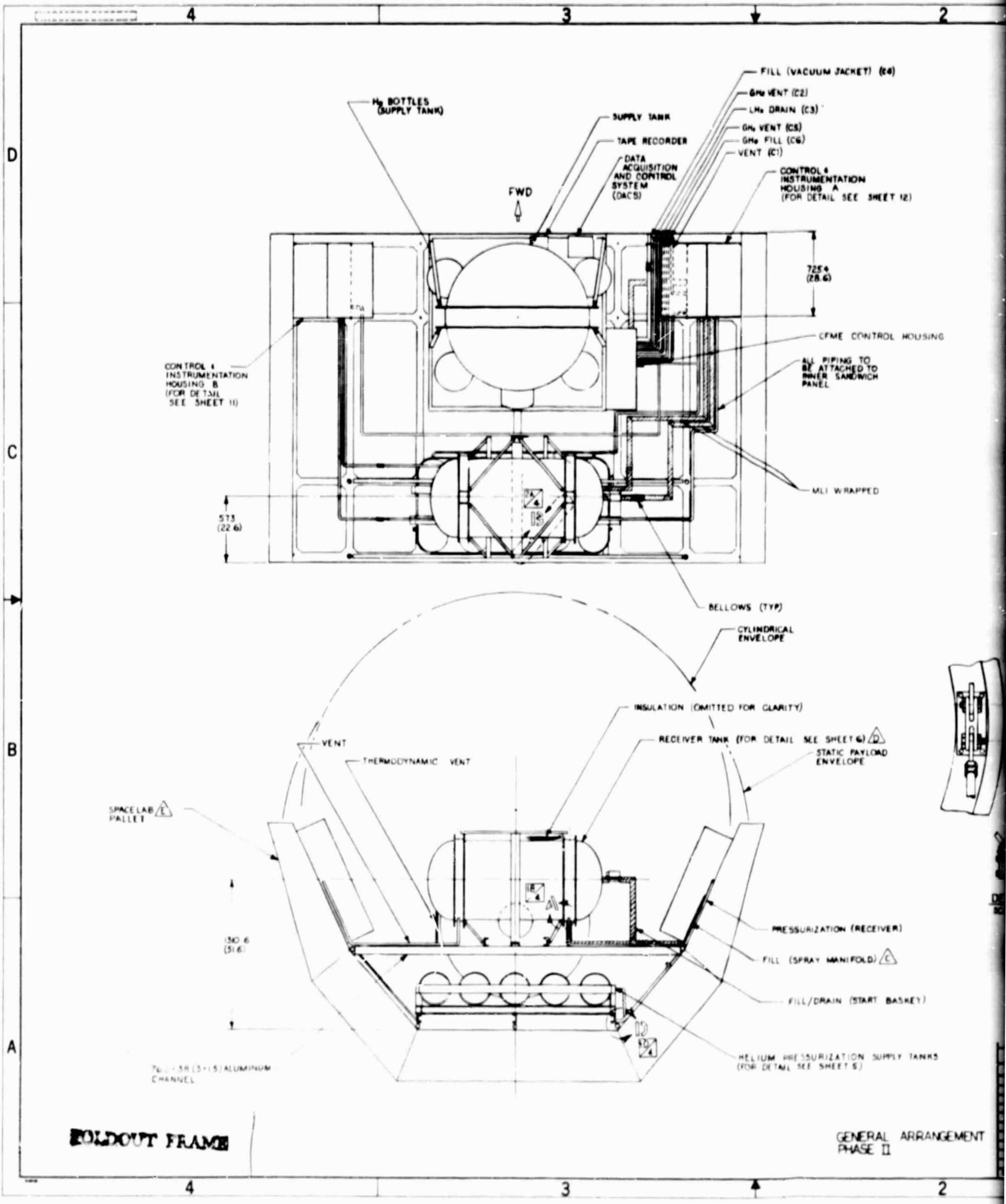
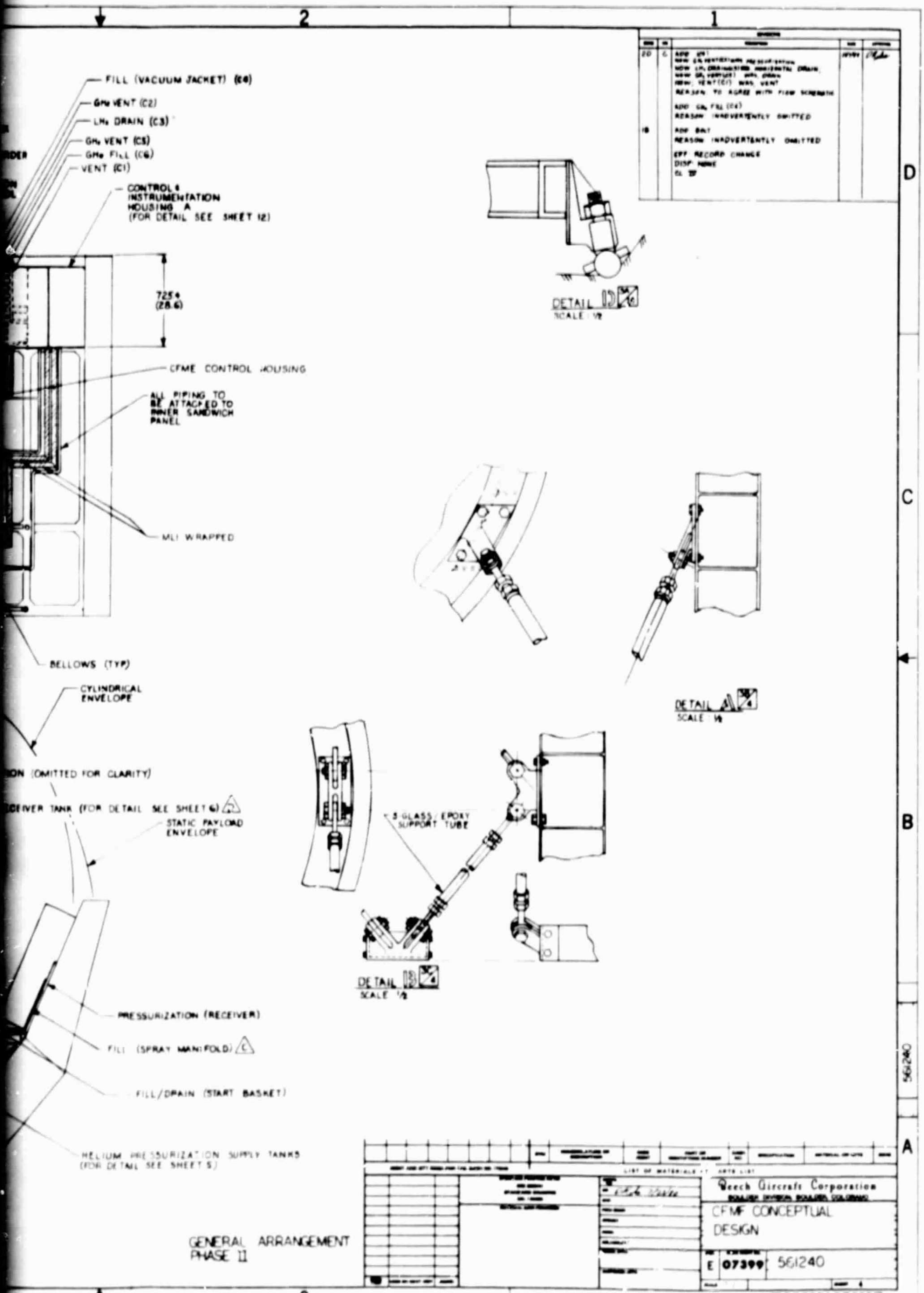


Figure 3-13 PHASE II GENERAL ARRANGEM



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-13 PHASE II GENERAL ARRANGEMENT

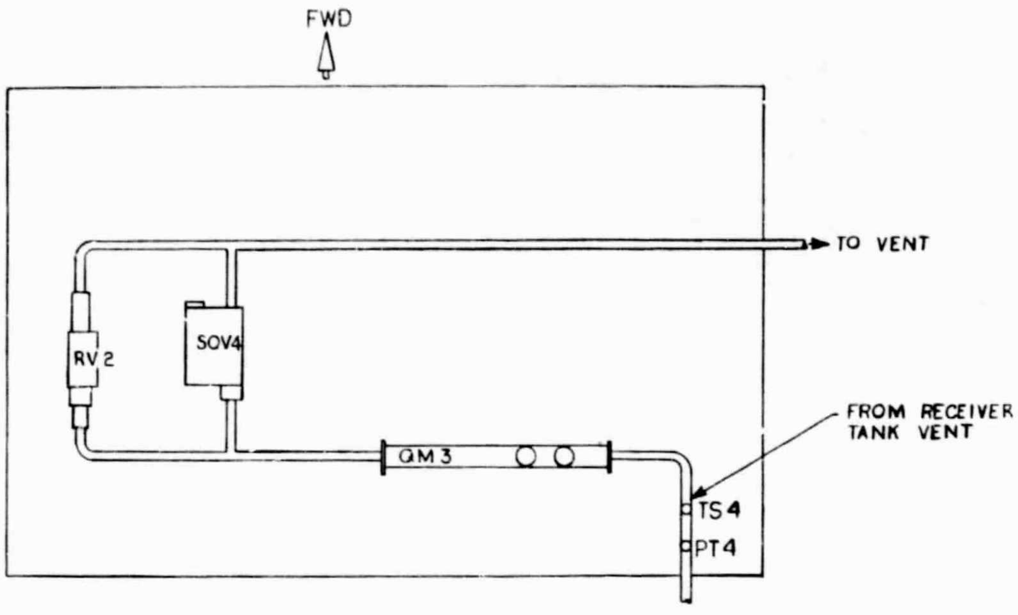

Figure 3-12 PHASE II INSTRUMENTATION AND CONTROL PALLET B

3.1.2 Phase II Design. Figure 3-13 shows the general arrangement of the Phase II facility on a Spacelab pallet, including the supply tank, receiver tank, helium pressurization bottles, and instrumentation and control panels. It should be noted that the Phase II facility utilizes the same helium pressurization subpallet as Phase I. The following paragraphs describe the flow schematic for Phase II and the supply and receiver tanks.

3.1.2.1 Flow Schematic. Figure 3-14 contains the Phase II flow schematic which was developed to ensure the experimental objectives of Phase II outlined in Table 2-II were met. Table 3-III contains a description of the function of each component. As in Phase I, safety considerations in the development of the flow schematic were to assure that no single component failure would result in an unsafe condition.

Phase II consists of missions two and three; the flow schematic in Figure 3-14 is for mission three. The second mission uses the same receiver tank without the start basket, the TVS with its externally wrapped heat exchanger and plumbing.

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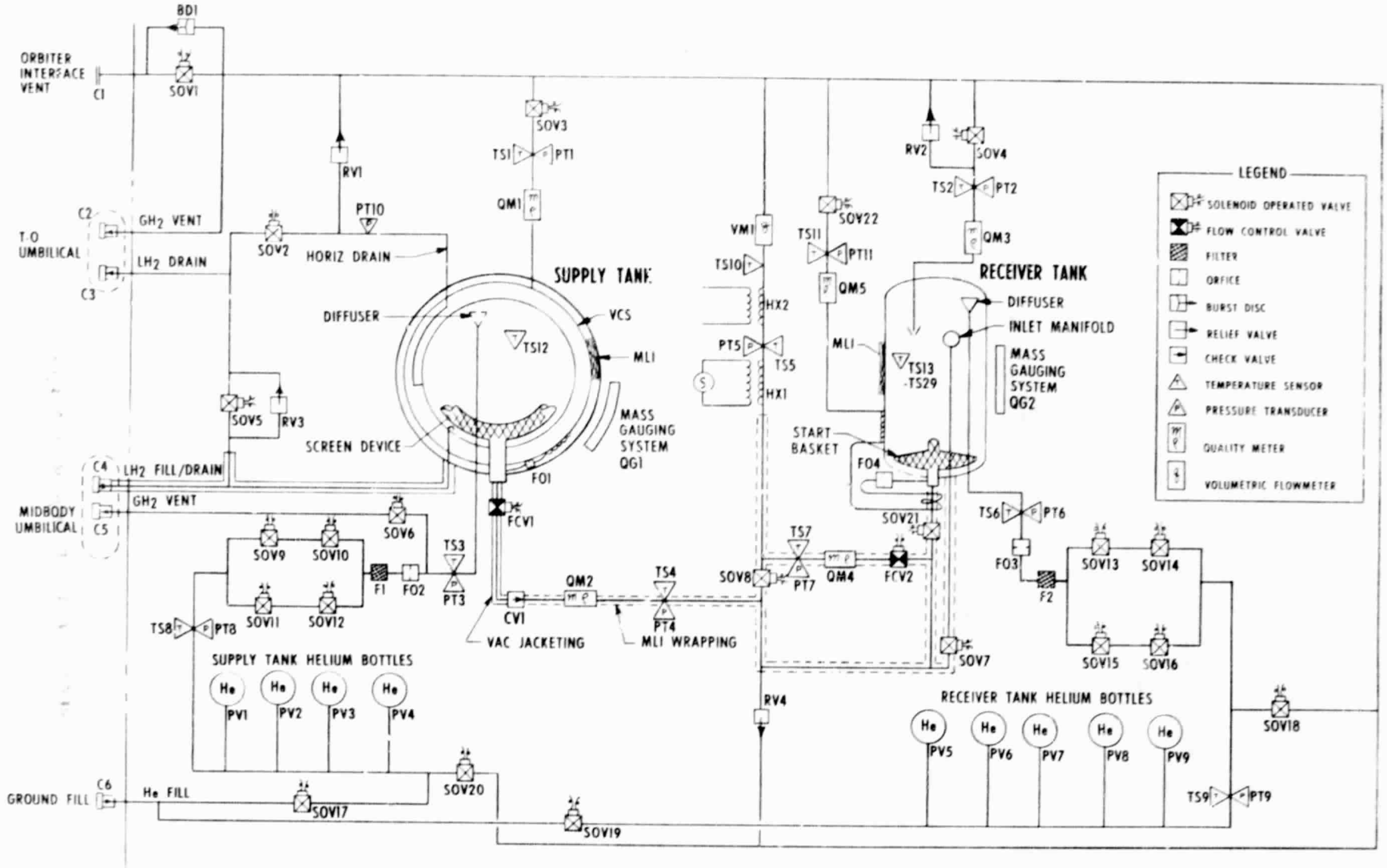

Figure 3-14 PHASE II FLOW SCHEMATIC

TABLE 3-III PHASE II FLOW SCHEMATIC COMPONENT FUNCTION

Component Identification Number	Data	Control	Function
SOV1		X	Opens upon orbit insertion to permit venting; closed during ground operations to allow venting through T-0 umbilical.
SOV2		X	Opens during horizontal drain operations; activated only when supply tank is loaded upon landing.
SOV3		X	Opens to permit operation of supply tank TVS.
SOV4		X	Allows receiver tank venting.
SOV5		X	Opens to permit supply tank ground drain at time < 4 hours by utilizing T-0 umbilical; closed during flight operation and ground fill.
SOV6		X	Open during supply tank fill; allows GH_2 venting during fill; closed during all other operations.
SOV7		X	Opens to allow LH_2 to enter receiver tank through inlet manifold; may be opened during emergency conditions resulting from receiver tank overpressurization.
SOV8		X	Opens during calibration of QM2; may be opened if receiver tank overpressurizes to provide additional venting capability.
SOV9		X	First valve in supply tank primary pressurization system; operates only when SOV10 is closed.
SOV10		X	Second valve in supply tank primary pressurization system; operates only when SOV9 is closed.
SOV11		X	First valve in supply tank backup pressurization system; operates only when SOV 12 is closed.
SOV12		X	Second valve in supply tank backup pressurization system; operates only when SOV11 is closed.
SOV13		X	Second valve in receiver tank primary pressurization system; operates only when SOV14 is closed.
SOV14		X	First valve in receiver tank primary pressurization system; operates only when SOV13 is closed.
SOV15		X	Second valve in receiver tank backup pressurization system; operates only when SOV16 is closed.
SOV16		X	First valve in receiver tank backup pressurization system; operates only when SOV15 is closed.
SOV17		X	Opens during supply tank helium bottle pressurization performed in KSC Operations and Control (O&C) Building.
SOV18		X	Allows venting of receiver tank helium bottles if an overpressurization condition is detected by PT9.
SOV19		X	Open during receiver tank helium bottle pressurization performed in KSC O&C Building.
SOV20		X	Permits venting of supply tank helium bottles if an overpressurization condition is detected by PT8.
SOV21		X	Opens during receiver tank fill to allow liquid to enter start basket, open during start basket outflow.
SOV22		X	Opens to operate receiver tank TVS.
FCV1			Controls supply tank outflow rate; opens during calibration of QM2, evaluation of supply tank capillary device and during receiver tank prechill.
FCV2			Controls receiver tank start basket outflow rate.
RV1			Prevents overpressurization of supply tank during all operations.
RV2			Protects receiver tank from overpressurization during all operations.
RV3			Protects supply tank from overpressurization during ground loading.
RV4			Protects transfer line components from overpressurization resulting from LH_2 boiling in closed line segment between FCV1, SOV8, SOV7 and SOV21.
BD1			Protects entire facility upon failure of SOV1; low pressure burst disk bursts at approximately 103 kPa (15 psid).
PT1	X		Supply tank TVS exiting pressure.
PT2	X	X	Receiver tank ullage vent pressure and tank pressure.
PT3	X		Supply Tank pressurization line pressure.
PT4	X		Transfer line pressure [illegible] supply tank outlet.

TABLE 3-III PHASE II FLOW SCHEMATIC COMPONENT FUNCTION (Concluded)

Component Identification Number	Data	Control	Function
PT5	X	X	Heat exchanger (HX1) pressure used to determine saturation temperature which controls heater input.
PT6	X		Receiver tank pressurization line pressure.
PT7	X		Transfer line pressure at receiver tank inlet.
PT8		X	Supply tank helium pressurization supply pressure.
PT9		X	Receiver tank helium pressurization supply pressure.
PT10	X	X	Supply tank pressure.
PT11	X	X	Receiver tank TVS exit pressure.
TS1	X		Supply tank TVS exit temperature.
TS2	X		Receiver tank vent ullage temperature.
TS3	X		Supply tank pressurization line temperature.
TS4	X	X	Transfer line temperature at supply tank outlet.
TS5	X	X	Heat exchanger (HX1) exit temperature; given PT5, this temperature is controlled to slightly greater than the corresponding saturation temperature.
TS6	X		Receiver tank pressurization line temperature.
TS7	X		Transfer line temperature at receiver tank inlet.
TS8		X	Supply tank helium pressurization supply temperature; used with PT8 and helium bottle volumes to determine helium quantity.
TS9		X	Receiver tank helium pressurization supply temperature used with PT9 and helium bottle volumes to determine helium quantity.
TS10		X	Exit temperature to heat exchanger (HX2) used to ensure that volumetric flow meter (VM1) measures vapor flow by controlling heat input.
TS11	X	X	Receiver tank TVS exit temperature.
QM1	X		Supply tank TVS exit flow quality and flow rate.
QM2	X	X	Supply tank outflow quality used to determine supply tank capillary device performance.
QM3	X		Receiver tank vent quality used to determine if liquid is vented.
QM4	X	X	Receiver tank start basket outflow quality.
QM5	X	X	Receiver tank TVS outflow quality.
VM1	X		Determines volumetric flow rate; used with quality determined from heat exchanger (HX1) to calibrate QM2.
FO1			Visco-jet used to provide isenthalpic expansion of supply tank TVS flow.
FO2			Restricts supply tank helium pressurant flow rate.
FO3			Restricts receiver tank helium pressurant flow rate.
F1			Filter used to prevent clogging of FO2.
F2			Filter used to prevent clogging of FO3.
QG1	X	X	Supply tank quantity measurement.
QG2	X	X	Receiver tank quantity measurement.
HX1			Heat exchanger for calibration of QM2.
HX2			Heat exchanger to insure vapor flow through VM1.

The first objective of Phase II, Mission Two, is receiver tank fill, which will be accomplished by the procedure outlined in Paragraph 2.2. The prechill charge is accomplished by opening FCV1 and SOV21 and allowing liquid to enter the receiver tank through the inlet manifold, then venting through SOV4. Following receiver tank fill, SOV7 will be opened to vent the transfer line to prevent overpressurization in the closed line segment between SOV7, SOV21 and FCV1.

The second objective of Mission Two is the demonstration of receiver tank refill capability by demonstrating on-orbit venting. The baseline approach is the use of a tapered vent tube which is operated by opening SOV4 and measuring the outflow quality with QM3. If significant quantities of liquid are vented during coast, SOV4 will be closed and the liquid hydrogen settled using the Reactant Control System (RCS) engines, during which SOV4 will be reopened.

The third objective is evaluation of the internal heat exchanger/fan TVS. Thermodynamic performance of the TVS and the ability of the fan to destratify and mix the bulk fluid in the tank will be assessed. Thermal performance will be determined by measuring the quality, temperature and pressure of the vent flow with QM4, TS7 and PT7. The effect of the fan on stratification and bulk fluid mixing will be evaluated by the temperature and pressure measurements made within the tank.

The primary objectives of Phase II, Mission Three, are: demonstration of a no-vent liquid fill of a fully configured receiver tank; start basket fill, outflow and refill performance. The no vent fill will be accomplished in the same manner as in Mission Two. The start basket fill will be accomplished during receiver tank fill by allowing flow to enter the receiver tank through both the inlet manifold and the start basket. Start basket fill and refill capability will be evaluated by outflowing through SOV21 and FCV2, and measuring outflow quality with QM4. The flow will then exit the Orbiter through an inactive HX1 and HX2.

3.1.2.2 Supply Tank. The Phase II supply tank is the Phase I supply tank described in Paragraph 3.1.1.2.

3.1.2.3 Receiver Tank. The receiver tank for Phase II, Mission Two, is a 0.165 scale POTV liquid hydrogen tank. It will contain an inlet manifold, helium diffuser, instrumentation tree, tapered vent tube, vapor pullthrough suppression baffle and an internal heat

exchanger/fan TVS. The Mission Three receiver tank is the same as the Mission Two, except that it will contain a propellant acquisition device in place of the suppression baffle, and an external heat exchanger for the TVS. Figure 3-15 shows the internal configuration of the Phase II, Mission Three, receiver tank. The drawing of the Phase II receiver tank is shown in Figure 3-16. The following paragraphs describe the subsystems which make up the 0.165 scale receiver tank.

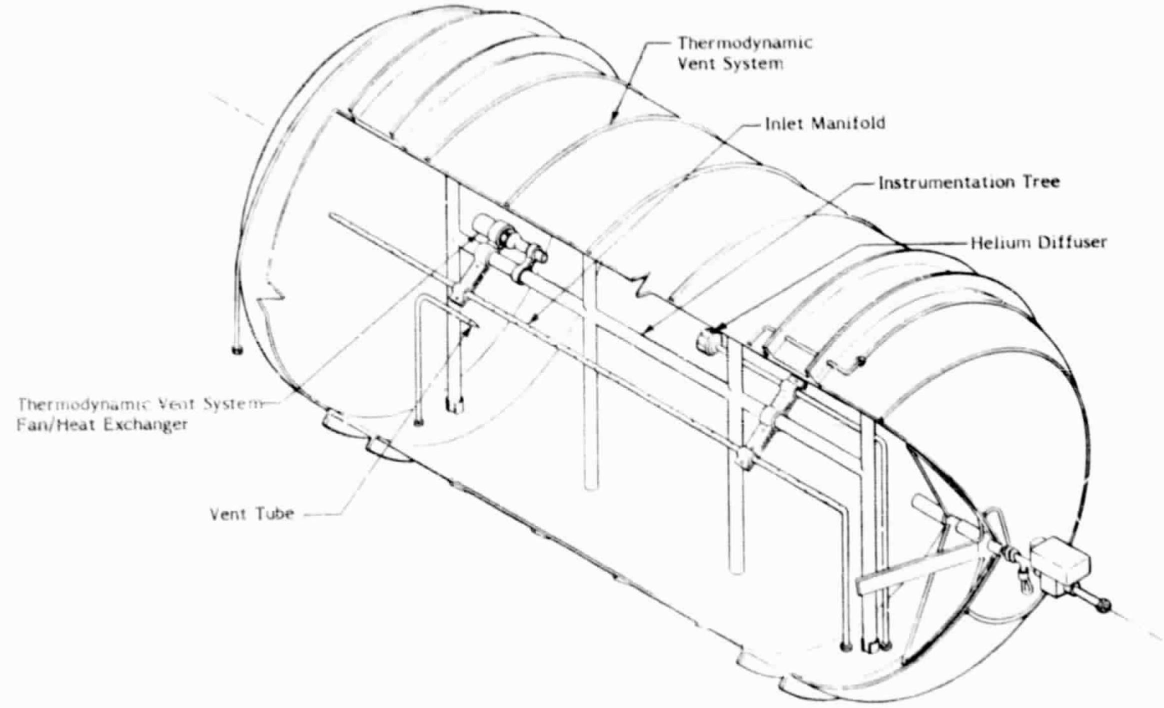

Figure 3-15 PHASE II. MISSION THREE, RECEIVER TANK INTERNAL CONFIGURATION

<u>Thermal Protection System</u>. The thermal protection system of the Phase II receiver tank consists of 20 layers of double-aluminized Kapton Superfloc, 8 S-glass/epoxy struts and a thermodynamic vent system. The insulation layup for the Phase II receiver tank is shown in Figure 3-17. This figure shows that eight gore sections per head and one cylindrical section are required. The details of the insulation-to-pressure vessel attachments and typical lap joints are contained in Figures 3-5 and 3-6, respectively. To allow evacuation

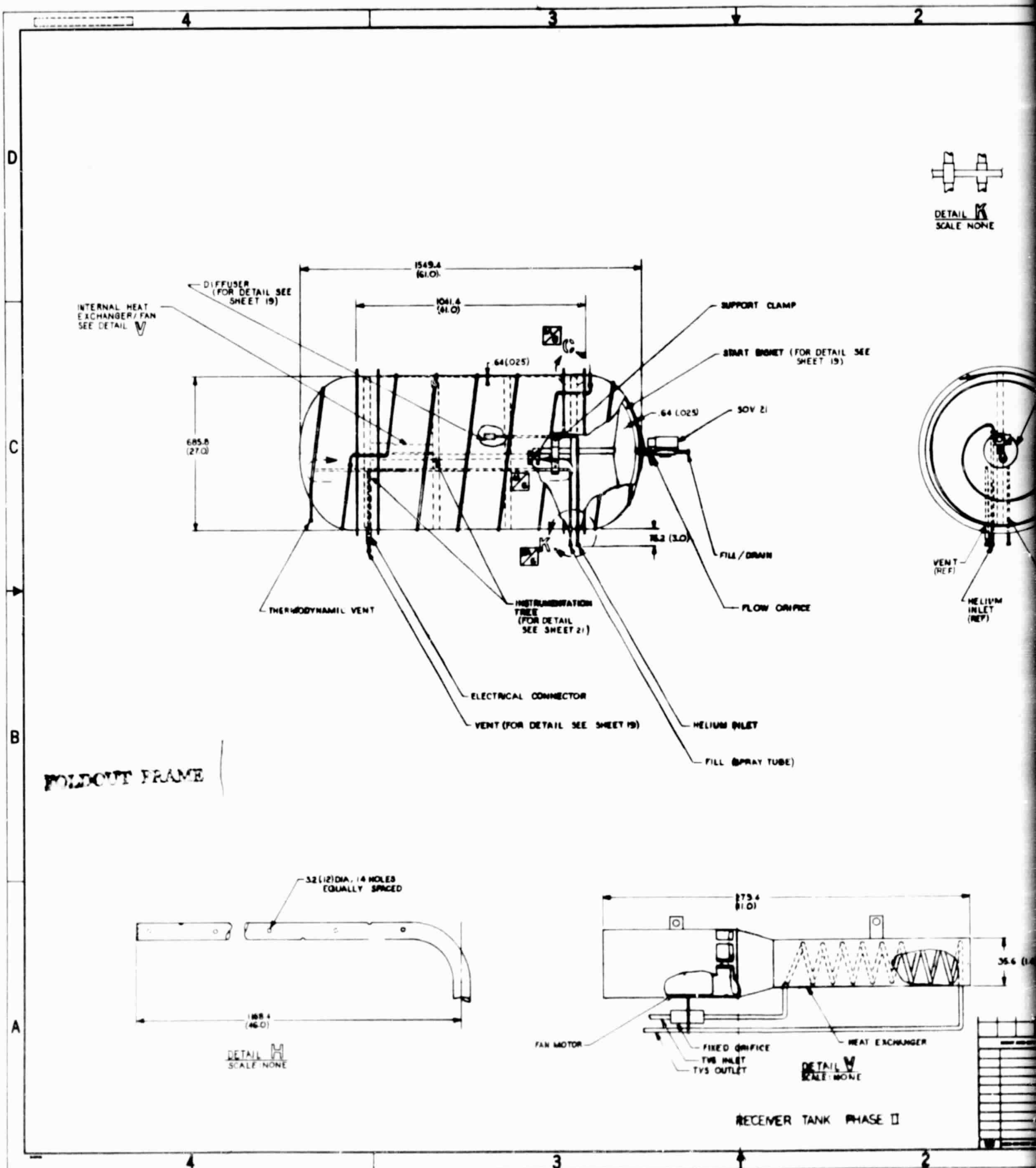

Figure 3-16 PHASE II, MISSION THREE, RECEIVER TA

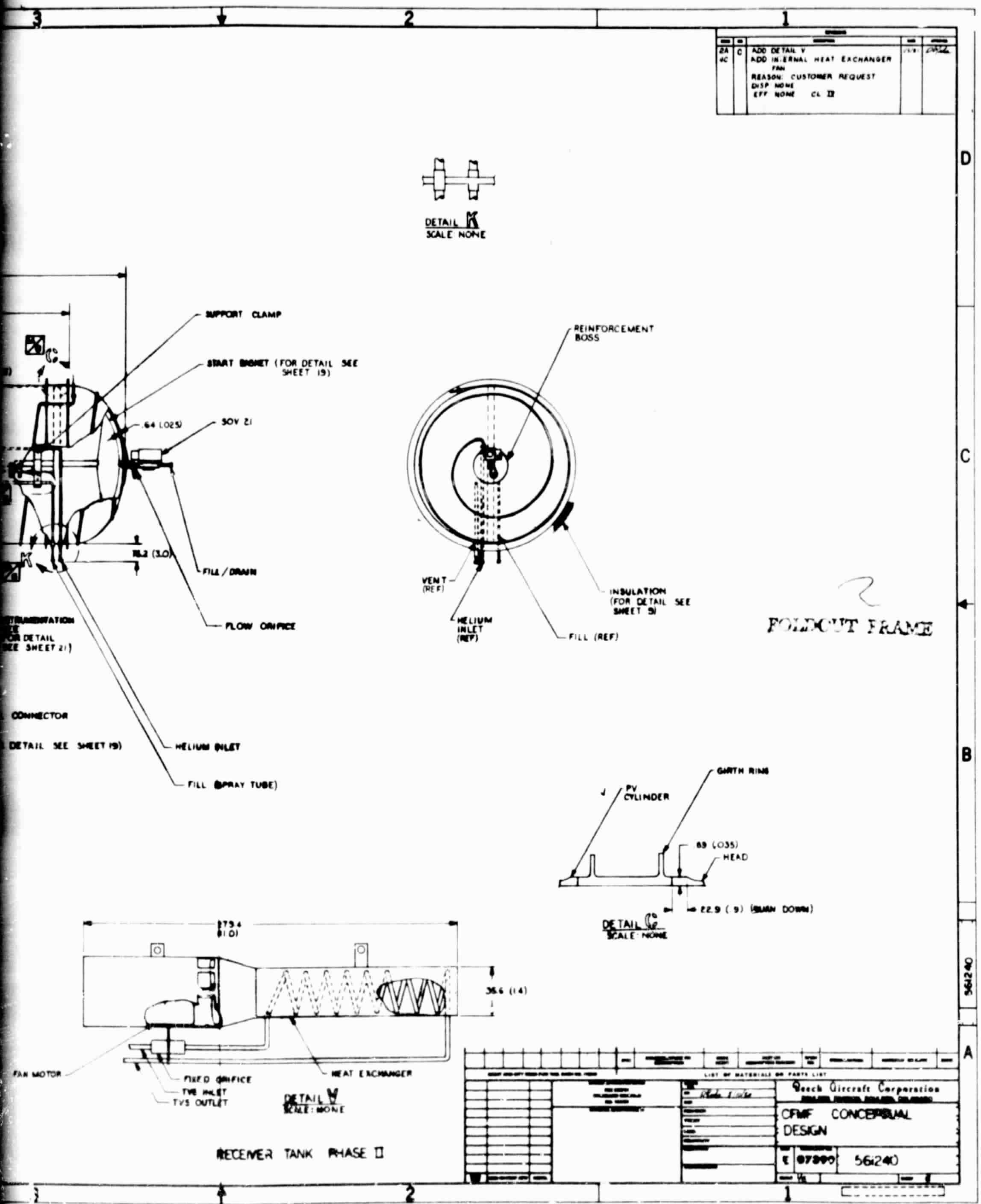

Figure 3-16 PHASE II, MISSION THREE, RECEIVER TANK

of the MLI during on-orbit operation, the insulation and the face sheet are perforated to approximately 0.5 percent opening. The tank is thermally isolated from its surroundings by the eight S-glass/epoxy struts.

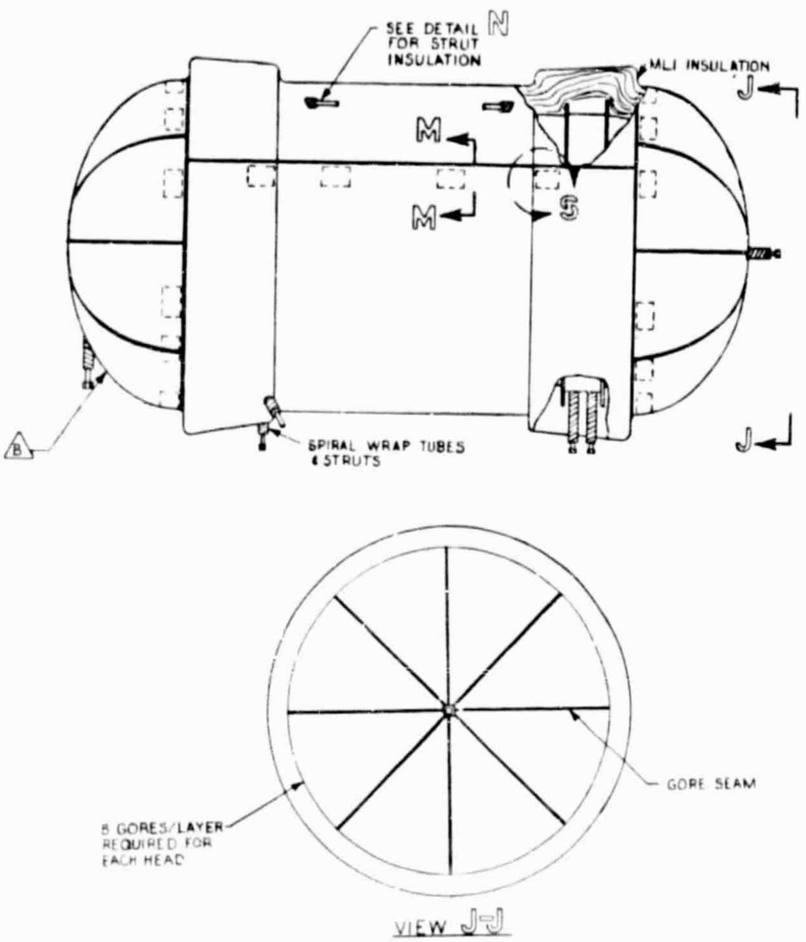

Figure 3-17 PHASE II TANK INSULATION

The TVS proposed for Phase II, Missions Two and Three, is shown schematically in Figure 3-18. The system is designed to vent only vapor with either vapor or liquid at the vent system inlet. During venting, fluid at the inlet is expanded to a low pressure and

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temperature, then passed through a compact heat exchanger before being vented overboard. In the heat exchanger, the vent fluid exchanges heat with the tank fluid. Ideally, in the heat exchanger, the vent fluid is completely vaporized and some of the tank fluid is liquefied. A small fan is used to force tank fluid through the heat exchanger and to mix the bulk fluid in the tank.

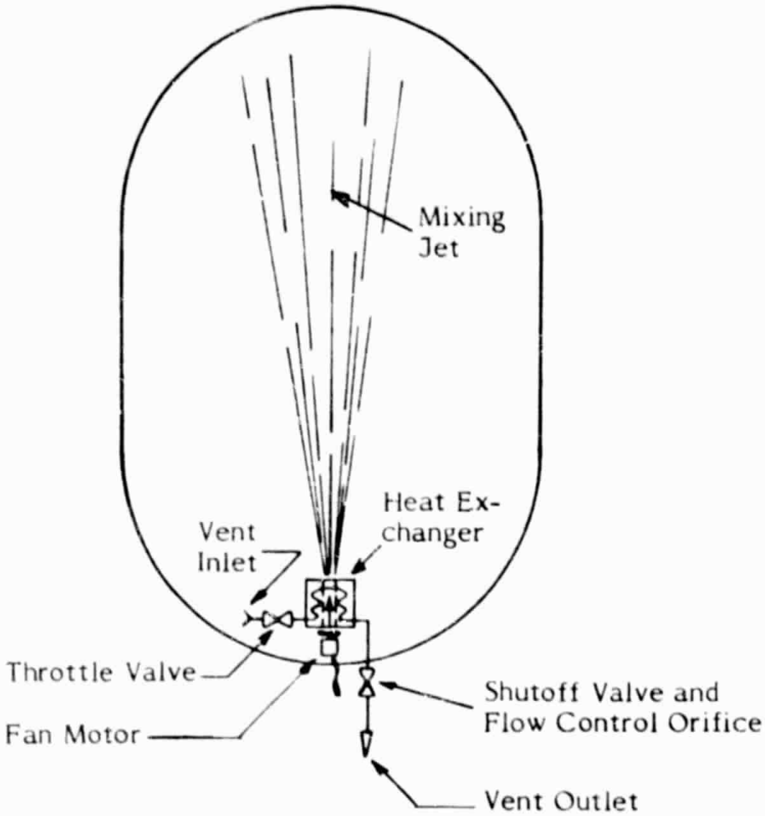


Figure 3-18 INTERNAL HEAT EXCHANGER/FAN THERMODYNAMIC VENT SYSTEM

Testing and analysis of this vent system have been discussed in some detail elsewhere (References 39, 40 and 41). Evaluation of system performance in zero-g will be a primary objective; the items to be evaluated include the following:

1. Occurrence of temperature stratification in the tank fluid during zero-g.
2. Ability of the fan to destratify and mix the bulk fluid in the tank.
3. Thermodynamic performance of the vent system.

An alternate vent system, shown in Figure 3-15, is proposed for evaluation during Phase II, Mission Three. In this vent system, liquid is withdrawn from the capillary device and, after passing through an expansion valve, circulates through a tube wrapped around the outside of the pressure vessel. The external tube system is easier to fabricate, more reliable since it is a completely passive system and potentially more efficient since no heat is added to the tank fluid by mixer motors. If stratification is not a problem and its weight is comparable to the internal TVS, then the external tube system may be preferable to the forced convection mixer system.

Support System. The receiver tank is mounted to its aluminum support system by eight S-glass/epoxy struts. The four struts on top of the tank restrain the tank in the X and Y direction. While the four lower struts support the tank in the Z and Y directions. The aluminum support system attaches to the Spacelab pallet hardpoints.

Pressure Control. The receiver tank pressure is maintained during outflow by the use of ambient helium pressurant. The baseline approach is identical to the pressurization system proposed for the supply tank. Concern over reliability in the cycling of the valves in the pressurization system led to consideration of an alternate pressure control systems using a pressure regulator and flow control valve shown in Figure 3-19. The pressure regulator reduces the inlet pressure to the required value and the flow control valve meters the flow into the tank. The solenoid valve protects the receiver tank in the event of a flow control valve failure. It is felt that this system offers superior reliability over the baseline approach and a more realistic pressurization system for the full scale POTV.

Inlet Manifold. The Phase II inlet manifold is similar to the Phase I manifold, except that it contains 18 holes.

Helium Diffuser. The helium diffuser proposed for Phase I will be used for Phase II.

Tapered Vent Tube. The purpose of the vent tube is to provide a passive means of venting hydrogen vapor and helium from the tank without settling. Satisfactory operation of the vent tube would simplify POTV operations and increase payload capability by reducing settling propellant requirements. Since the vent tube would be utilized prior to a refill operation, it is anticipated that a substantial quantity of vapor will be present in the tank at initiation of venting.

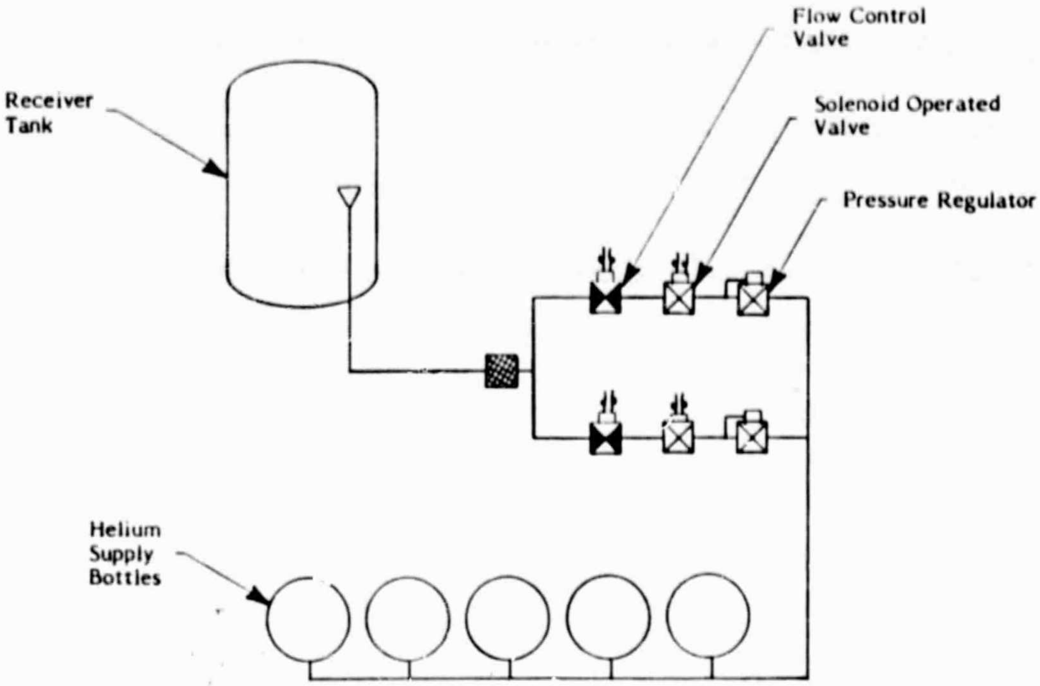


Figure 3-19 ALTERNATE PRESSURIZATION SYSTEM

The vent tube, shown in Figure 3-9, has a conical frustrum-shaped tip extending into the ullage region. Liquid present at the vent inlet will not accumulate, but will flow over the outside surface due to the action of surface tension forces. The shape of an arbitrary volume of liquid (having a zero contact angle) on a cylinder, as shown in Figure 3-20, is based on calculations previously performed for an S-IVB capillary device application. This figure shows the low-g shapes of three globules as a function of the parameter $\Delta P \times R_o/\sigma$. Globules cannot continue to spread without bounds over a tube surface but approach a spherical shape limiting its maximum size. By increasing the size of the liquid globule on the vent tube, it would be possible to eventually enclose the vent tube with liquid. The conical frustrum tip of the vent tube provides some assurance that little, if any, liquid will be vented overboard during low acceleration coasts because the shape of the tip is such that surface tension forces will cause liquid to flow away from the tube inlet. The shedding of liquid from a tapered tube has been demonstrated and was reported in Reference 42. Liquid/vapor sensors using this principle were flown on a Titan-Centaur. The tapered vent tube represents an untried approach to venting; however, testing of the tapered vent tube will not jeopardize Phase II missions since venting can be accomplished with settling.

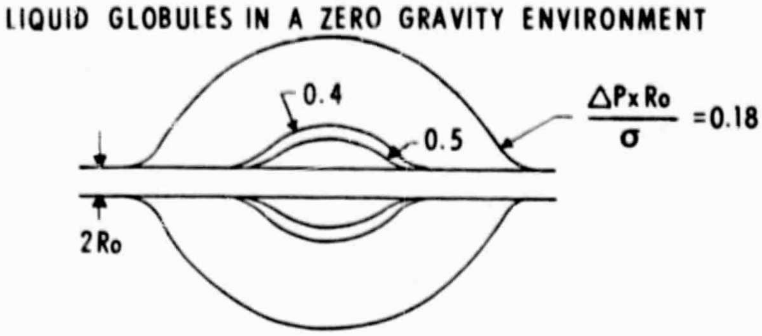


Figure 3-20 LIQUID GLOBULE ON A CYLINDER IN A ZERO-GRAVITY ENVIRONMENT

Propellant Acquisition System. The propellant acquisition system consists of a start basket mounted over the outlet of the 0.165 scale tank as shown in Figure 2-21. Conceptually, the start basket design is similar to that described in Reference 43 for the full-scale POTV tank. The bottom of the basket is an ellipsoidal surface conforming to the shape of the head of the 0.165 scale POTV tank. The top is a 6° cone which is supported by stiffeners to resist settling loads. The main screens are two layers of mesh backed by 51 percent open area perforated plates. The two plate-screen layers are

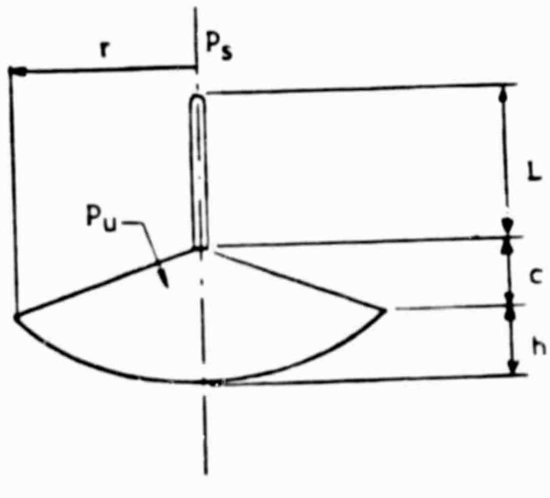


Figure 3-21 START BASKET GEOMETRY

separated by a gap of 5.3 mm (0.21 in) to provide a wicking path to replace liquid evaporated from the surface of the basket during zero g. The conical part of the basket is topped by a formed screen standpipe. The function of the standpipe is to allow vapor to escape during refill of the start basket and to enter the start basket during periods of zero g when liquid is evaporating from its surface. Screen covered channels inside the start basket ensure that only vapor-free liquid is withdrawn from the tank during operation.

The major design considerations for the design of a start basket were discussed in Paragraph 2.7.2.4. Table 3-IV summarizes the specific design constraints for the 0.165 scale POTV tank start basket. The settling acceleration level shown in Table 3-IV is based on the -Y axis acceleration produced by the main RCS thrusters (see Table 2-VIII). It was assumed that disturbing accelerations in the +Y direction are limited to vernier thruster levels. If the disturbing accelerations were equal to the maximum settling acceleration, then it would not be possible to design the start basket to retain liquid during a disturbing acceleration and refill after settling. When the tank is less than 60 percent full, the start basket will not refill since the static head in the tank is not large enough to drive vapor from the standpipe. With the tank more than 60 percent full, preliminary calculations show that the start basket should be refilled within one minute after settling is initiated.

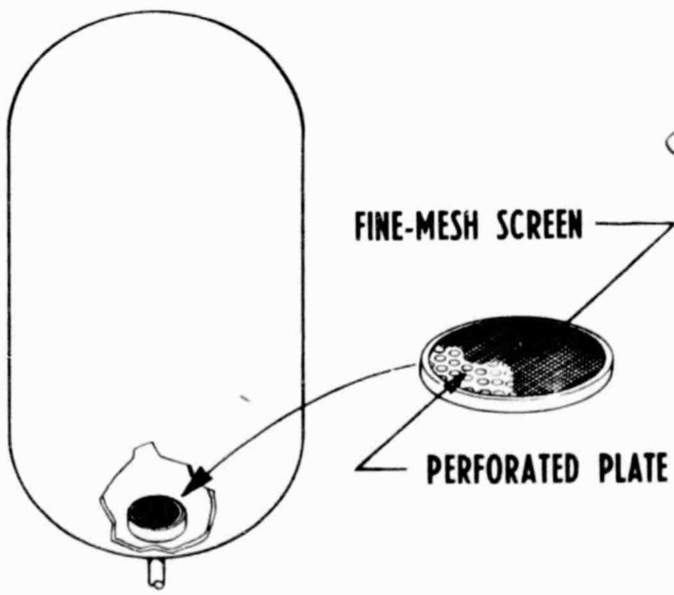
TABLE 3-IV 0.165 SCALE POTV TANK START BASKET DESIGN CONSTRAINTS

Tank:	0.165 Scale POTV Tank
	Overall Length = 1533.9 mm (60.39 in)
	Diameter = 695.7 mm (27.39 in)
	Elliptical Heads With Major/Minor Axis Ratio of 1.38
Fluid:	LH_2 at $20^{\circ}K$ ($36^{\circ}R$)
Flowrate:	Propellant Outflow Rate = 0.02 kg/sec (0.05 lbm/sec)
Acceleration:	Maximum Settling Acceleration = 0.22 m/s^2 (0.7 ft/sec^2) along -Y-axis due to RCS main thrusters
	Maximum Disturbing Acceleration = 0.002 m/s^2 (0.007 ft/sec^2) along +Y-axis due to RCS vernier thrusters
Duration of Zero g:	Liquid will be retained in start basket for ten hours maximum.

(See Appendix III). Based on the start basket design analysis discussed in Paragraph 3.2.6, the dimensions of a conical-elliptical start basket were calculated to give the required volume of 0.0060 m^3 (0.213 ft^3). Using the nomenclature of Figure 3-21:

r	= 223.3 mm (8.79 in)
h	= 61.7 mm (2.43 in)
c	= 23.4 mm (0.92 in)
L	= 502.9 mm (19.8 in)

Vapor Pullthrough Suppression. In the first mission of Phase II, the 0.165 scale receiver tank will not contain a capillary liquid acquisition device; it will be drained while settling using the RCS thrusters. During low gravity draining, premature vapor ingestion may occur resulting in excessive residuals. This phenomenon was investigated in Reference 44 and a functional relationship between the liquid residuals and the ratio (Weber number)/(Bond number plus one) was observed. For an outflow of 22.7 gm/sec (0.05 lb/sec) and an acceleration level of 0.22 m/sec^2 (0.72 ft/sec^2), the Weber and Bond numbers are 1.00×10^{-3} and 3282, respectively. The ratio $W/(B + 1) = 3.0 \times 10^{-7}$ does not fall on the curve (Figure 7 in Reference 44); however, assuming zero-g (B = 0), the corresponding residual is 7 percent. In the actual case (B = 3282) the residuals would be less. If required to insure minimum residuals, a fine mesh screen with a perforated backing plate could be located over the tank outlet. This screened outlet configuration is illustrated in Figure 3-22.



C-2

Figure 3-22 VAPOR PULLTHROUGH SUPPRESSION BAFFLE

Instrumentation Tree. Figure 3-23 contains a drawing of the Phase II instrumentation tree. The tree construction is identical to the Phase I instrumentation tree. The tree center pole is offset to allow room for the start basket standpipe. During final design of the instrumentation tree, its effect on the liquid behavior during low-g and settling will have to be assessed.

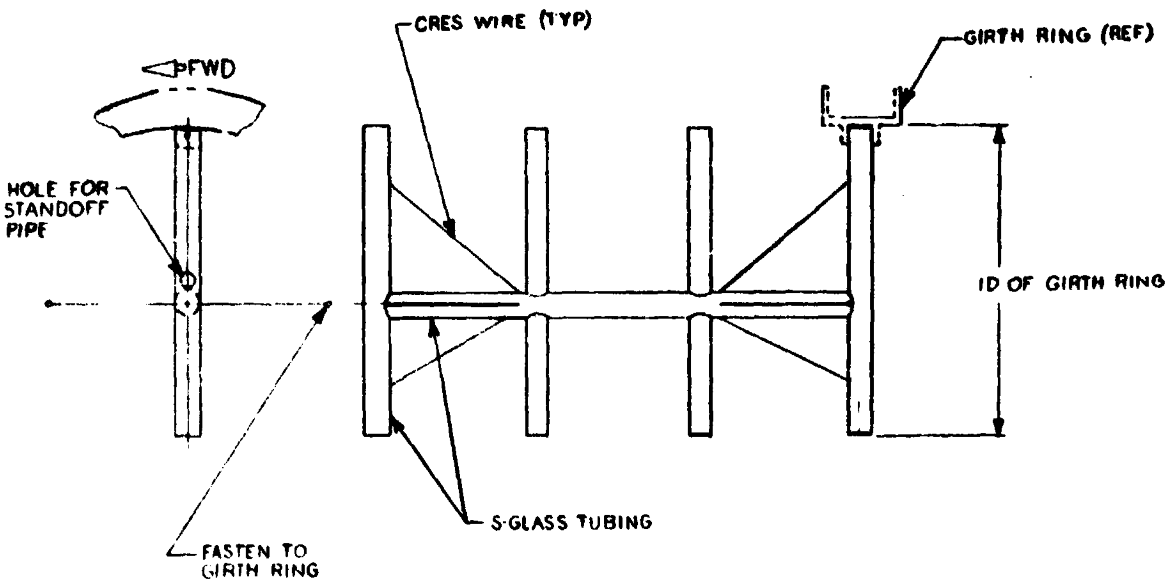


Figure 3-23 PHASE II RECEIVER TANK INSTRUMENTATION TREE

3.1.2.4 Instrumentation and Control Pallets. Instrumentation and Control Pallets A and B are illustrated in Figures 3-24 and 3-25, respectively; their location in the Spacelab pallet is shown in Figure 3-13.

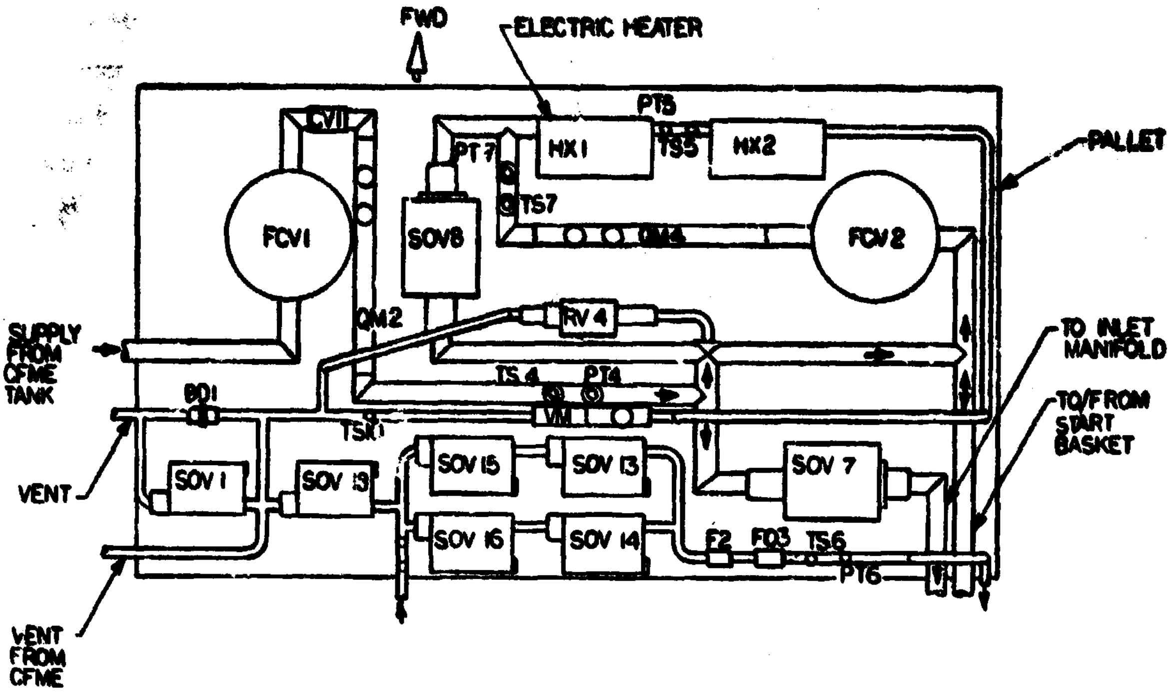


Figure 3-24 PHASE II INSTRUMENTATION AND CONTROL PALLET A

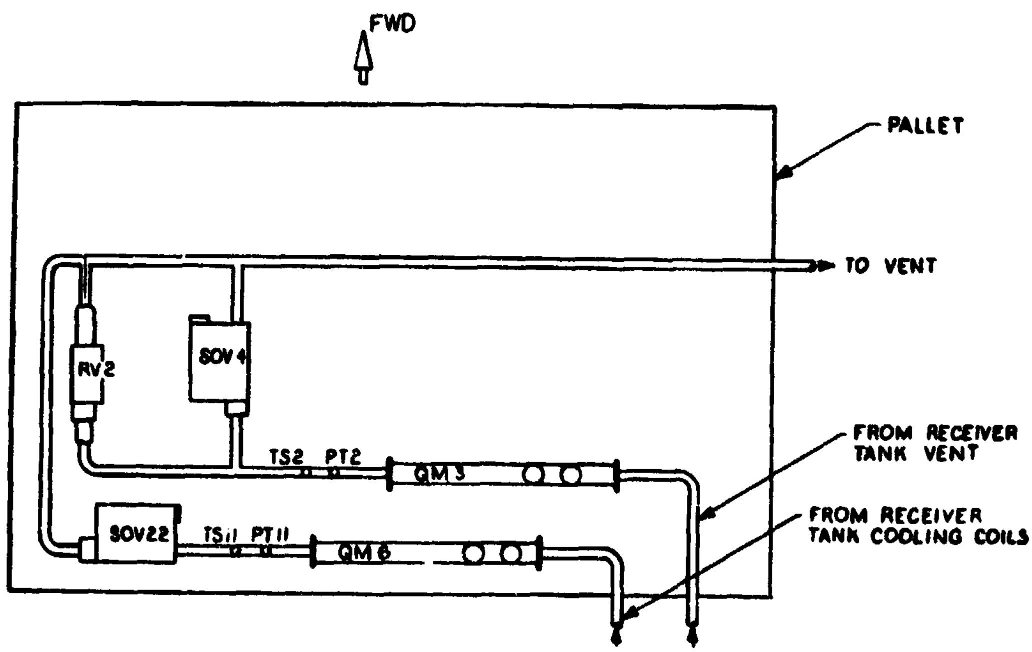


Figure 3-25 PHASE II INSTRUMENTATION AND CONTROL PALLET B

3.1.3 Instrumentation. The instrumentation required to monitor the experiment temperatures, pressures, LH_2 mass flow rates, LH_2 quantity and local accelerations is described in the following paragraphs. The temperature and pressure measurements determine the thermodynamic state of the fluid. Pressure transducer PT10 is used to determine the supply tank pressure. Temperature sensors in the receiver tank are used to measure the tank temperatures. The mass flow rates are measured by fluid quality flow meters which determine density and volumetric flow rate. The fluid quantity in the supply and receiver tanks may be measured by a nucleonic mass gauging system which detects the attenuation of low-level radiation by the fluid. An accelerometer will be used to detect the acceleration levels during coast and RCS thruster firing.

Temperature Sensors. Platinum resistance temperature sensors are sufficiently sensitive over the temperature range of interest (14K to 400K) to allow all the temperature measurements to be made with a single power supply and signal conditioner. Table 3-V is an example of the resistance of a typical 500-ohm platinum temperature sensor as a function of temperature. For each sensor, individual calibration tables at intervals of 10° or less will be used. The recommended calibration intervals are 1°K from 13K to 23K, 5°K from 23K to 100K and 10°K from 100K to 400K. Sensors with an ice-point resistance of 500 ohms are recommended for cryogenic sensitivity, coupled with low power requirements. Four terminal temperature sensors are recommended for the temperature measurements for three reasons: First, the use of four terminals minimizes the error due to lead resistances in the measurement of the temperature. Second, the separation of the current terminals from the potential measuring terminals permits the wiring of a number of temperature sensors in series, reducing the number of constant current power supplies required to operate the temperature sensors. Third, the use of four terminal temperature sensors simplifies the wiring of the temperature sensors within the receiver tank. A typical receiver tank temperature schematic is shown in Figure 3-26 with the current terminals at FE1 and FE2, and the potential terminals at FE3 through FE11. The junction between the temperature sensors FE12 through FE20 would be located inside the receiver tank.

TABLE 3-V RESISTANCE OF A TYPICAL 500 OHM PLATINUM TEMPERATURE SENSOR

T (°K)	R (ohm)	T (°K)	R (ohm)
10	0.51	220	393.48
20	2.30	240	433.89
40	21.08	260	474.04
60	57.58	280	513.94
80	100.12	300	553.60
100	143.48	320	593.01
120	186.38	340	632.18
140	228.68	360	671.12
160	270.45	380	709.50
180	311.79	400	747.97
200	352.79		

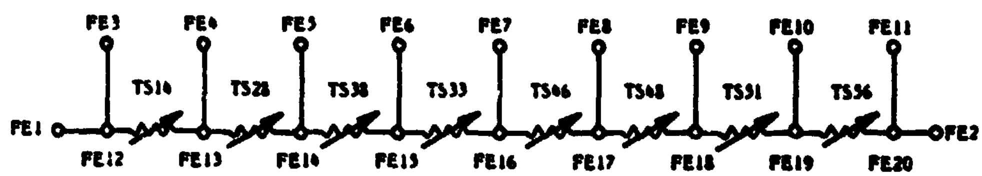


Figure 3-26 TYPICAL RECEIVER TANK TEMPERATURE SENSOR SCHEMATIC

Temperature Sensors External to Receiver Tank. Immersion type temperature sensors can be used for all the externally mounted temperature sensors, except TS4 and TS7, in both phases of the experiment. Surface mounted temperature sensors will be used for TS4 and TS7 to measure transfer line temperatures. These temperature sensors will be located downstream of the quality meters to prevent their heat leak from interfering with the quality measurements. The external temperature sensors will be divided into two groups to minimize the number of power supplies required to operate them. Group A consists of those sensors associated with the supply tank, Group B with the receiver tank. The groups are identified in Table 3-VI per the labeling of the flow schematics, Figures 3-2 and 3-14.

TABLE 3-VI EXTERNAL TEMPERATURE SENSOR GROUPS

(Supply Tank) A	(Receiver Tank) B
TS 1	TS 2
TS 3	TS 6
TS 4	TS 7
TS 5	TS 9
TS 8	TS11
TS10	

Internal Temperature Sensors. Surface mount temperature sensors will be used within the receiver tank. Fifty-two temperature sensors, listed in Table 3-VII, will be used in Phase I and located as shown in Figure 3-27. The temperature sensors are located at 14 different levels within the receiver tank. The first two levels, starting at the lower end of the tank, contain TS13 and TS14 at the helium and liquid hydrogen inlets. The third level is near the midlevel of the lower head and contains four temperature sensors evenly spaced on the pressure vessel. The fourth level contains one temperature sensor (TS19) at the first outlet of the LH_2 fill manifold.

The sensors at the fifth, eighth, eleventh and twelth levels are mounted on or near the instrumentation tree. There are nine sensors on each of these four levels. Four of the sensors are mounted to the pressure vessel wall or the girth rings, and are evenly spaced. One sensor is mounted at the intersection of the tree support rod and the cross bar. The other four sensors are mounted on the cross bar at one-third and two-thirds of the radius of the tank. The sensors at the sixth, ninth and tenth levels are located on the LH_2 inlet manifold and are evenly spaced between the lowest LH_2 inlet and at the end of the manifold. The sensor at the seventh level is located at the helium diffuser. The four sensors at the thirteenth level are evenly spaced on the upper head and the last sensor is at the top of the pressure vessel. The dimensions given in Table 3-VII are approximate and can be varied to obtain the optimum mounting and data.

TABLE 3-VII PHASE I CFMF TEMPERATURE SENSOR LOCATIONS

Level	Temperature Sensor	R (mm)	Θ (radians)	Z (mm)	Level	Temperature Sensor	R (mm)	Θ (radians)	Z (mm)
1	TS13	48	2.50	6	8	TS39	768	3 /2	1337
2	TS14	90	5.76	9	9	TS40	48	2.50	1523
3	TS15	576	0	168	10	TS41	48	2.50	1980
3	TS16	576	$\pi/2$	168	11	TS42	0	0	2041
3	TS17	576	π	168	11	TS43	256	0	2041
3	TS18	576	$3\pi/2$	168	11	TS44	256	π	2041
4	TS19	48	2.50	610	11	TS45	512	0	2041
5	TS20	0	0	633	11	TS46	512	π	2041
5	TS21	256	0	633	11	TS47	768	0	2041
5	TS22	256	π	633	11	TS48	768	$\pi/2$	2041
5	TS23	512	0	633	11	TS49	768	π	2041
5	TS24	512	π	633	11	TS50	768	$3\pi/2$	2041
5	TS25	768	0	633	12	TS51	0	0	2746
5	TS26	768	$\pi/2$	633	12	TS52	256	0	2746
5	TS27	768	π	633	12	TS53	256	π	2746
5	TS28	768	$3\pi/2$	633	12	TS54	512	0	2746
6	TS29	48	2.50	1067	12	TS55	512	π	2746
7	TS30	90	5.76	1317	12	TS56	768	0	2746
8	TS31	0	0	1337	12	TS57	768	$\pi/2$	2746
8	TS32	256	0	1337	12	TS58	768	π	2746
8	TS33	256	π	1337	12	TS59	768	$3\pi/2$	2746
8	TS34	512	0	1337	13	TS60	576	0	3209
8	TS35	512	π	1337	13	TS61	576	$\pi/2$	3209
8	TS36	768	0	1337	13	TS62	576	π	3209
8	TS37	768	$\pi/2$	1337	13	TS63	576	$3\pi/2$	3209
8	TS38	768	π	1337	14	TS64	0	0	3377

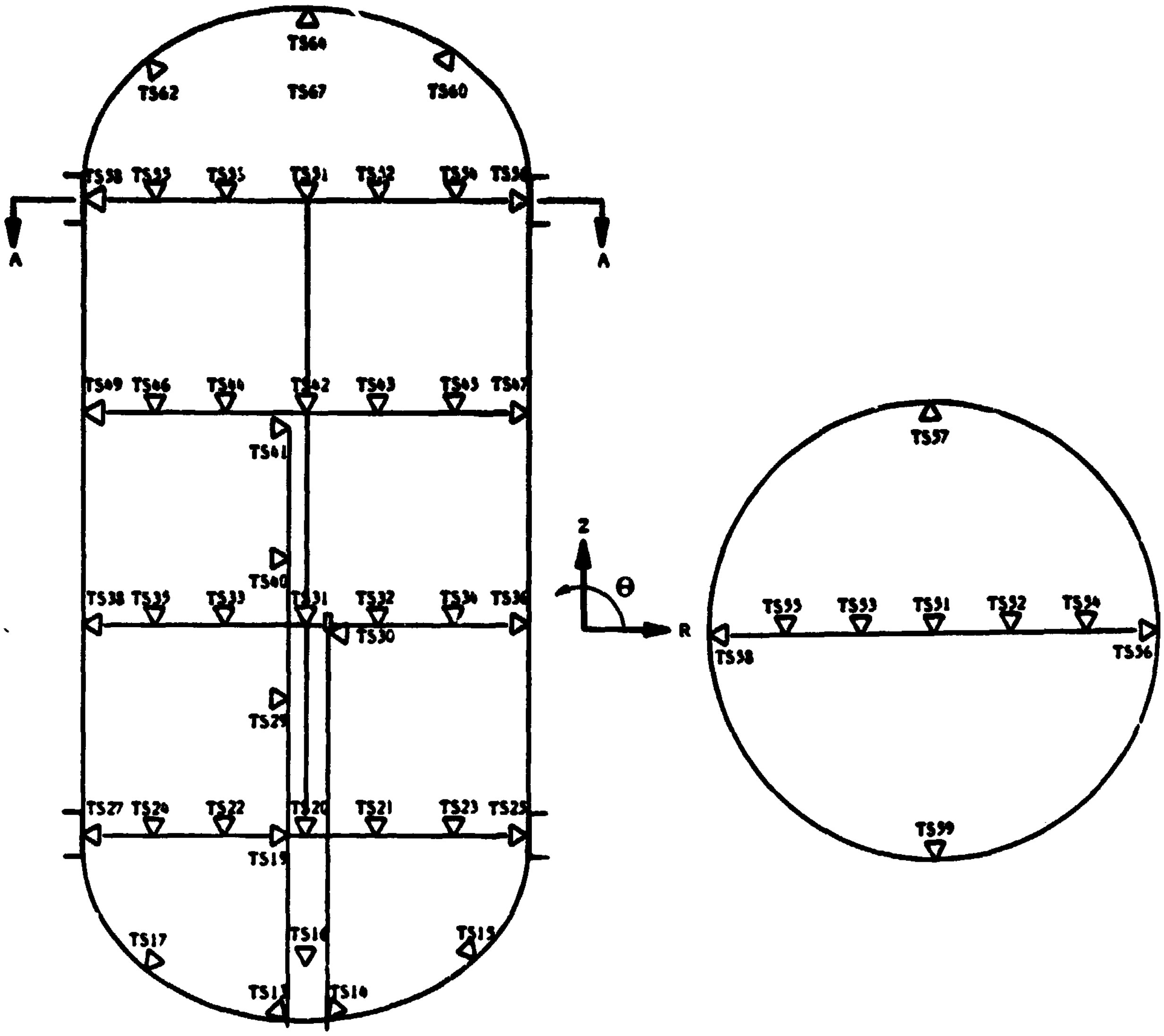


Figure 3-27 CFMF TEMPERATURE SENSOR LOCATIONS
PHASE I - RECEIVER TANK

Thirty-five temperature sensors are used in the receiver tank for Phase II. The sensors are located at 12 different levels and in a similar pattern to those in Phase I. The major difference between the Phase I and Phase II receiver tank temperature instrumentation is the temperature sensors used to monitor the temperature distribution in the start basket. The locations of the sensors are given in Figure 3-28 and in Table 3-VIII.

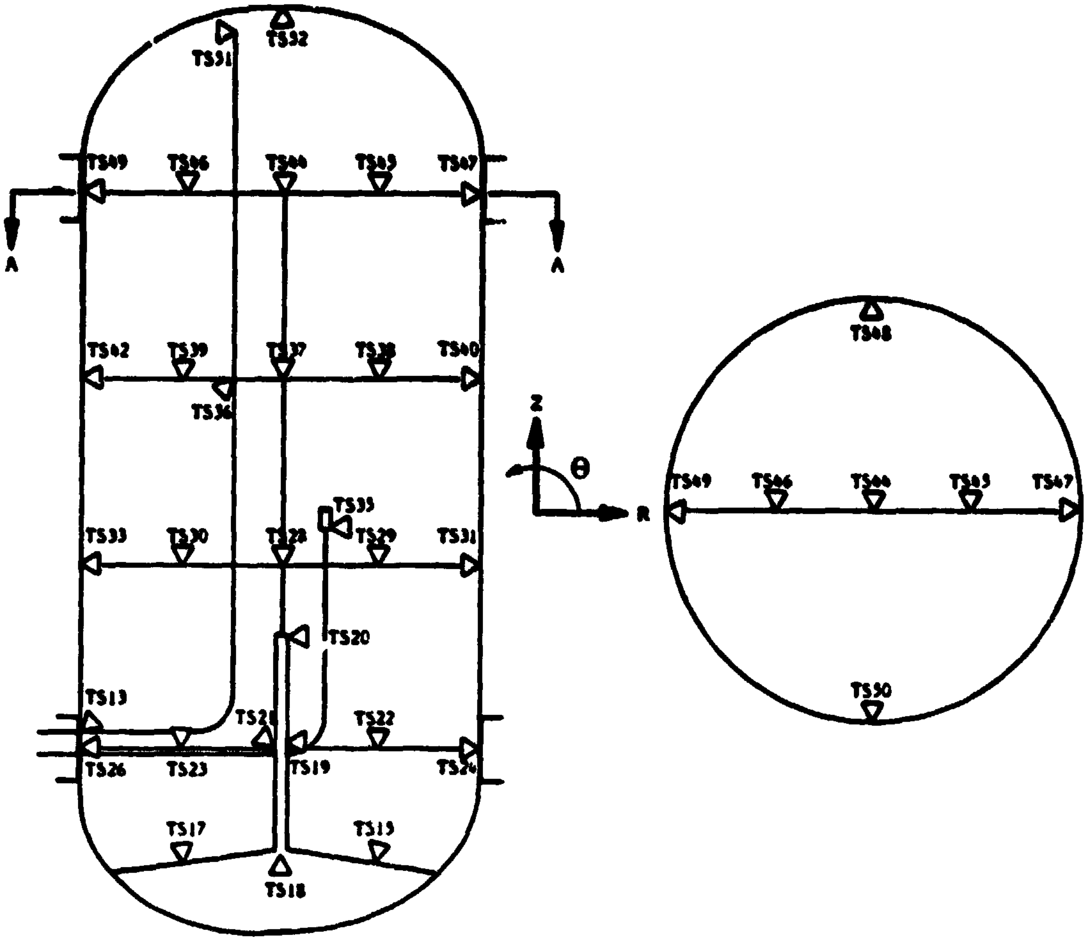


Figure 3-28 CFMF TEMPERATURE SENSOR LOCATIONS
PHASE II - RECEIVER TANK

The temperature sensors will be grouped to reduce the number of power supplies and separate the sensors at the various levels to reduce the probability of losing a significant amount of data with a temperature sensor circuit failure. The recommended groupings of the temperature sensors are given in Table 3-IX.

TABLE 3-VIII PHASE II CFMF TEMPERATURE SENSOR LOCATIONS

Level	Temperature Sensor	R (mm)	Θ (radians)	Z (mm)	Level	Temperature Sensor	R (mm)	Θ (radians)	Z (mm)
1	TS13	343	3.04	336	8	TS33	343	π	618
2	TS14	343	3.24	300	9	TS34	343	3π/2	618
3	TS15	120	0	120	10	TS35	84	5.88	678
3	TS16	120	π/2	120	11	TS36	87	2.67	929
3	TS17	120	π	120	11	TS37	0	0	931
3	TS18	120	3π/2	120	11	TS38	171	0	931
4	TS19	12	0	315	11	TS39	171	π	931
5	TS20	12	0	498	11	TS40	343	0	931
5	TS21	0	0	305	11	TS41	343	π/2	931
5	TS22	171	0	305	11	TS42	343	π	931
5	TS23	171	π	305	11	TS43	343	3π/2	931
5	TS24	343	0	305	11	TS44	0	0	1245
5	TS25	343	π/2	305	12	TS45	171	0	1245
5	TS26	343	π	305	12	TS46	171	π	1245
5	TS27	343	3π/2	305	12	TS47	343	0	1245
5	TS28	0	0	618	12	TS48	343	π/2	1245
6	TS29	171	0	618	12	TS49	343	π	1245
7	TS30	171	π	618	12	TS50	343	3π/2	1245
8	TS31	343	0	618	12	TS51	87	2.67	1512
8	TS32	343	π/2	618	12	TS52	0	0	1549

TABLE 3-IX CFMF TEMPERATURE SENSOR GROUPS

Phase I Receiver Tank

Group A	TS13, TS30, TS60, TS57, TS49, TS39, TS21, TS34, TS52
Group B	TS19, TS15, TS63, TS61, TS58, TS50, TS22, TS35, TS53
Group C	TS29, TS25, TS16, TS20, TS62, TS59, TS23, TS43, TS54
Group D	TS40, TS36, TS26, TS17, TS31, TS64, TS24, TS44, TS55
Group E	TS41, TS47, TS37, TS27, TS18, TS42, TS32, TS45
Group F	TS14, TS56, TS48, TS38, TS28, TS51, TS33, TS46

TABLE 3-IX CFMF TEMPERATURE SENSOR GROUPS (Concluded)

Phase II Receiver Tank

Group A	TS13, TS16, TS17, TS18, TS19, TS20, TS30, TS21
Group B	TS14, TS25, TS26, TS27, TS28, TS29, TS39, TS22
Group C	TS15, TS32, TS33, TS34 TS40, TS38, TS46, TS37
Group D	TS24, TS41, TS42, TS43, TS47, TS45, TS35, TS44
Group E	TS31, TS48, TS49, TS50, TS52, TS23, TS36, TS51

Temperature Sensor Power Supply. Eight power supplies with the capability of delivering 30 milliwatts each at a constant current of 2 milliamperes will suffice for all the temperature sensors. This power requirement is based on the resistance of the sensors at 400K. The power dissipation in the receiver tank will be substantially less at cryogenic temperatures because of the reduced resistance of the temperature sensors. The power dissipation for a 2.3-ohm temperature sensor at 2 milliamps will be 9.2 microwatts per sensor. With 54 temperature sensors in the receiver tank, the total power dissipation will be 496.8 microwatts. Although a single power supply could provide the current requirements of the temperature sensors, it is advisable to use multiple power supplies to avoid the loss of data due to single power supply failure.

Temperature Sensor Signal Conditioner. The signal conditioning for the temperature sensors will consist of amplifying the detected voltages to a level which is consistent with analog-to-digital conversion. The amplified signal can then be multiplexed and converted to a digital signal for processing through the DACS for storage and/or control purposes. When the signal is used as a control signal, it will be compared to previously determined levels for the purpose of generating the control signal. The temperature sensor signal conversion to engineering units will be accomplished from the recorded data on the ground.

Pressure Transducers. Three types of pressure transducers will be required for the experiment: Internally and externally compensated absolute pressure transducers and differential pressure transducers. All three will be of the bonded strain gauge type of transducer. Most of the cryogenic and all of the ambient pressure transducers will include compensation resistors to linearize the bridge output. This configuration is standard to

the pressure transducers considered for this application. Two of the cryogenic pressure transducers (PT4 and PT7) will be mounted directly in the transfer line. They are externally compensated pressure transducers and their compensation circuitry must be maintained at ambient temperature.

Differential pressure transducers will be mounted in the start basket to measure the pressure drop across the screen. This will require a differential pressure transducer which can accurately measure a pressure of 1.4 KPa (0.2 psid) to 3.4 KPa (0.5 psid) at 14K (25°R). The compensation for the differential transducer would be located external to the receiver tank at ambient temperature.

Pressure Transducer Power Supply. A nearly constant voltage of 10 vdc will be required for the pressure transducers. Regulation within 0.1 v will reduce the power supply's contribution to the measurement error to approximately the same magnitude as that of the expected rms error from the transducer. A single power supply for all transducers has the advantage that the relative contribution to measurement error can be minimized, but lacks backup capability. The recommended solution is to provide a second power supply that automatically switches in if the primary power supply fails.

Pressure Transducer Signal Conditioning. Signal conditioning for the pressure transducers will be similar to that for the temperature sensors, except the compensation circuits will provide a nearly linear output. The signals for data acquisition and control will be amplified to a level compatible with analog-to-digital conversion and the reduction to engineering units will be accomplished during data analysis.

Quality Meter. The quality meter is available with signal conditioning to provide output signals for the mass flow rate, integrated mass flow, density and void ratio. The same quality meters will be used for flow measurements in both Phase I and Phase II. The only differences between individual quality meters will be the flow rate capacity. Each quality meter consists of a turbine type flow meter and a dielectric measurement device. The dielectric measurement device measures the fluid density and density oscillations. The density oscillations are used to detect two-phase flow and measure the void ratio of the LH_2.

Accelerometer. An accelerometer will be required to detect the acceleration of the receiver tank during coast and RCS engine firing. An electrostatic accelerometer is available which measures accelerations in the range of 10^{-2} g to 10^{-9} g.

Mass Gauging. A mass gauging system is required to determine the mass of hydrogen in the receiver tank during Phase II. A nuclear radiation technique offers the advantage that it responds directly to the mass of fluid in the tank (i.e., the greater the mass, the more the radiation is attenuated). Since the gauge is sensitive to the mass it is, in theory, independent of the density and, therefore, variations in density throughout the bulk of the fluid. This feature makes the nuclear gauging system attractive because the problem is reduced to designing a radiation source which irradiates the entire volume of the tank rather than confining the fluid to a particular region. The nuclear gauging system consists of a Kr-85 radiation source, contained within an aluminum tube, and a detector; the layout of the tubular radiation source and the location of the detector are unique to each tank design.

3.1.4 Valves. All valves, with the exception of the flow control valve at the supply tank outlet, will be 24 vdc solenoid operated. High speed, ambient temperature valves are required in the helium pressurization system; the cryogenic system uses both vacuum jacketed and unjacketed cryogenic valves. These valves are identified by type in Table 3-X for both the Phase I and Phase II facilities.

Solenoid Operated Valves. All solenoid valves will be normally closed, continuous duty valves. The ambient temperature pullthrough time, at operating pressure, is 80 milliseconds for the normal speed valves and 15 milliseconds for the high speed helium pressurization system valves.

Each solenoid valve will be equipped with two position indicator switches: One to indicate the full open position and one to indicate the full closed position. The switches will be wired as shown in Figure 3-29 so that a single data bit can be used to record the valve position. The voltage V_2 will appear as the position signal covering the entire range between full open and full closed. Selecting resistors R1 and R2 so that V_2 is between the maximum logic '0' voltage and the minimum logic '1' voltage will give an unstable signal which can be used to indicate the valve transition or to determine if the valve is stuck in an intermediate position.

TABLE 3-X VALVE REQUIREMENTS

	Unjacketed				Vacuum Jacketed			
	Normal		High Speed		Normal		Flow Control	
Valve Identifier	Phase I	Phase II	Phase I	Phase II	Phase I	Phase II	Phase I	Phase II
SOV1	X	X						
SOV2	X	X						
SOV3	X	X						
SOV4	X	X						
SOV5	X	X						
SOV6	X	X						
SOV7					X	X		
SOV8					X	X		
SOV9			X	X				
SOV10			X	X				
SOV11			X	X				
SOV12			X	X				
SOV13			X	X				
SOV14			X	X				
SOV15			X	X				
SOV16			X	X				
SOV17	X	X						
SOV18	X	X						
SOV19	X	X						
SOV20	X	X						
SOV21						X		
FCV1							X	X
FCV2								X

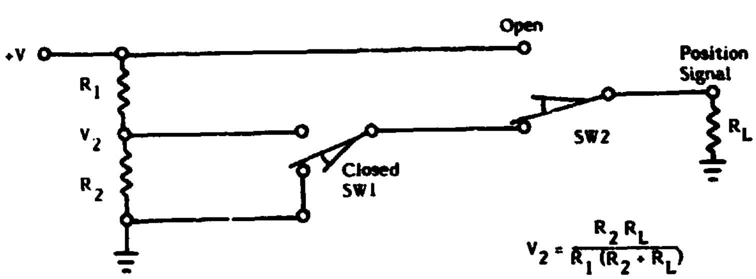


Figure 3-29 SOLENOID VALVE POSITION INDICATOR

Flow Control Valves. The flow control valves will be operated by stepper motors for accurate and reproducible positioning. A valve position counter will indicate the valve position in addition to discrete full open and full closed position indicators. Valve position will be determined by counting the number of pulses to the valve using the counter in a count up mode for valve opening and a count down mode for valve closing. The valve will be positioned by comparing the position counter with a predetermined position until the difference is zero. The valve position counter will automatically be reset to zero whenever the full closed position indicator is activated. The purpose of this reset is to provide a means of accurately restarting the valve position counter in the event of a power failure or other transient event which could invalidate the data in the counter.

3.1.5 Experiment Data and Control. The experiment data and control system employs a microprocessor-based, on-board Data Acquisition and Control System (DACS) to provide experimental control while collecting and recording the data. All electrical instrumentation and control equipment will be connected to the DACS. Parallel interconnections to the Spacelab Caution and Warning (C&W) System and the Remote Acquisition Unit (RAU) of the Data Command and Management System (DCMS) will be used as required. The parallel interconnections to the C&W System will alert the Payload Specialist/Mission Specialist to any potentially hazardous condition and allow additional control. The parallel interconnections to the RAU allow the condition to be monitored independently of the DACS.

The DACS is designed to operate the experiment and reduce crew workload. The proposed DACS design is a flexible system capable of communicating with the Spacelab DCMS allowing economical software implementation of additional control through the Spacelab DCMS. The DACS has two primary functions: (1) Data acquisition and recording and (2) experiment control. At the appropriate time during countdown, the GSE will transmit the current time to the DACS clock and command the experiment DACS to begin recording. The recording process will continue until commanded to stop by the GSE (normally after completion of the flight) or by loss of power (recording will resume when power is returned).

Status latches will be provided to record the operating mode of the DACS. In the event of a loss of power, the status latches and the status of various sensors will determine the DACS response when power is restored.

The block diagram shown in Figure 3-30 illustrates the central functions of the DACS. Operation will begin with a power on interrupt. The microprocessor will then perform all necessary initialization, including obtaining Greenwich Mean Time (GMT) for the DACS internal clock from the Spacelab DCMS.

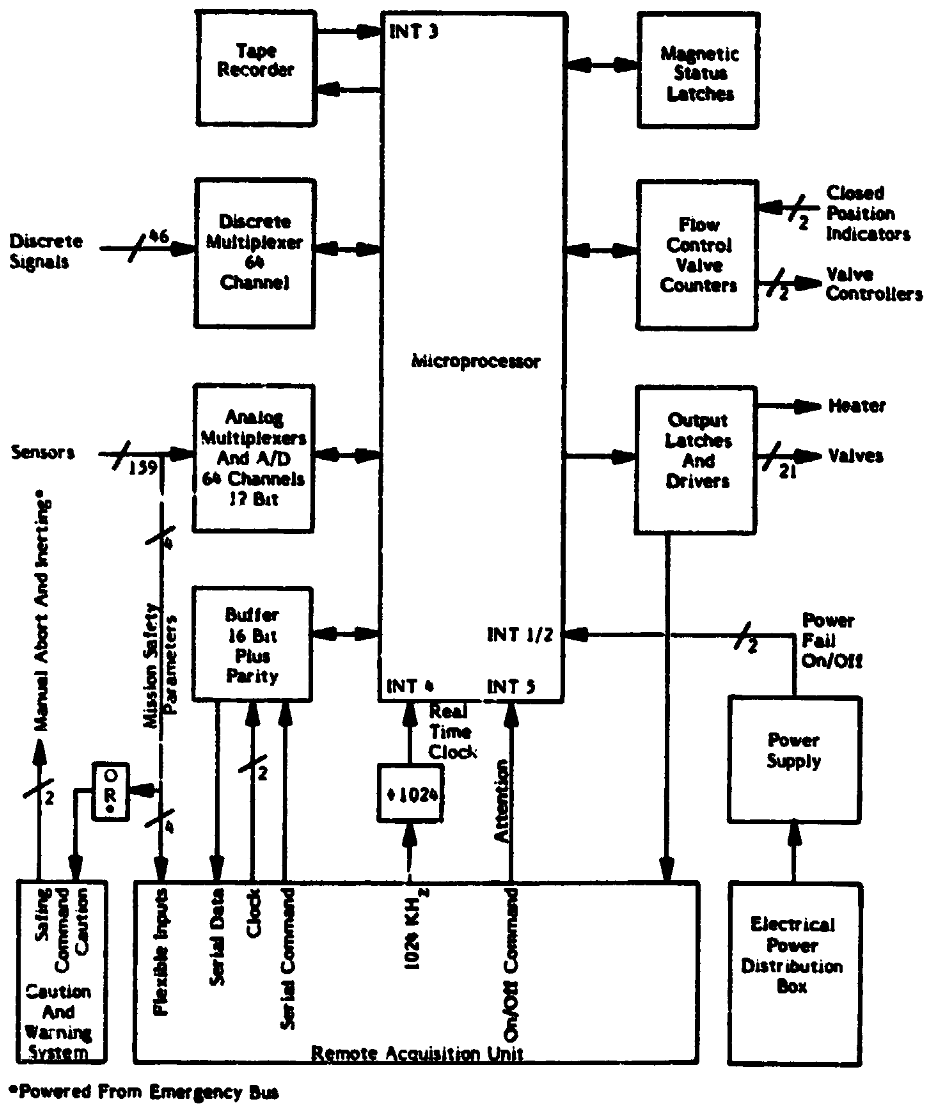


Figure 3-30 DATA ACQUISITION AND CONTROL SYSTEM BLOCK DIAGRAM

The interface between the DACS and the DCMS will be handled in a word-at-a-time mode. The interface will be controlled by the DCMS; however, either system may initiate

a transfer. The DCMS initiates a data or command transfer by sending a command to the buffer and then raising the attention line shown in Figure 3-30. The DACS responds to the DCMS command by placing data or status in the buffer and raising the request line. The DCMS will then lower the attention line, read the buffer, place data, status or a new command in the buffer and raise the attention line again. This process ends when the DCMS and DACS acknowledge each other's end of transmission commands. The DACS initiates transmission by raising the request line. The operation will then continue as described above with the DCMS issuing an inquiry command to the buffer and raising the attention line.

After being initialized, the DACS clock is updated periodically with the 1024 KHz User Time Clock. Figure 3-30 shows a one-millisecond update rate, which is obtained by dividing the 1024 KHz Clock by 1024. The optimum clock rate will be determined by the instrumentation and data collection analysis.

The outputs of several sensors (i.e., those which may affect mission safety), will be sent to the DCMS via the RAU flexible inputs to allow independent monitoring in the event of DACS failure. If any of these sensors indicate a hazardous condition, a caution signal will be sent to the C&W System. A Safing Command will be used to abort and inert the experiment in the event a DACS failure prevents a normal programmed shutdown. The safing command will drain and inert supply and receiver tanks.

The DACS will use a power-off interrupt to assure an orderly shutdown of the microprocessor. An unplanned power-down will not allow time for the DACS to change the experiment operating mode; however, after the resumption of power, the microprocessor will interogate the magnetic status latches to determine the last operating mode of the experiment, update the DACS internal clock, poll the experiment sensors and resume control of the experiment.

DACS Operation. During ground fill and prelaunch checkout, the DACS will be operating under control of GSE to assist in monitoring and controlling the experiment. The system must be designed to be powered down whenever necessary during this phase.

When prelaunch checkout of the experiment is complete, the DACS will assume complete operation of the experiment in either the experiment "on" or "off" mode. Prior to lift-off and continuing through ascent, the experiment will be in the off mode. In this mode, the DACS will only transmit to the recorder.

The DACS software will use a table-driven, real-time executive. The executive performs interrupt handling, system initialization, module scheduling and real-time clock support. Modules are autonomous program segments which perform a given function and are run at regular intervals upon request of another module, or in response to an interrupt. The executive will scan the Executive Control Table (ECT) and select the next module to be run, and then call a processing module to perform the required function and return control back to the executive. Each control table entry will contain a module name, priority code, timer and the status of all required inputs to the module. The timer will be decremented at the real-time clock rate. A module is ready to run when its timer has decremented to zero and all necessary input conditions are met, and it is the highest priority module which is ready to run. All modules of one priority which are ready to run execute before control passes to a lower priority modulus. ECT priorities may be dynamically reassigned by the executive.

Data Acquisition. The data required for experiment control and analysis of the experiment operation will be processed through two types of channels. One type of channel will accept discrete data where each bit represents the status of a particular component, such as a solenoid valve or heater. A logic '1' will represent the on or powered status and a logic '0' will represent the off or unpowered status. A general description of the logic levels is illustrated in Figure 3-31. The actual voltages and times will depend on the specific microprocessor used, but a logic '0' must be within V0 (minimum) and V0 (maximum), and a logic '1' must be between V1 (minimum) and V1 (maximum) for a minimum time (t (min)) in order to be correctly recognized. Other definitions are possible where the signal is the transition from one level to the next or the levels are inverted. The second type of channel is an analog channel where the signal is an analog voltage which represents the temperature, pressure or other parameter. The analog voltage is converted to a digital signal compatible with the microprocessor. Either type channel can be selected, one at a time, by the microprocessor by multiplexing all the inputs to a single input and assigning a unique address to each sensor input. The data will then be read by the DACS and used for control or data storage, depending on the operating mode and which portion of the program is executing at the time the data is read.

Data Storage. Data to be stored will be assigned an identification code which, in the case of a sensor, could be the sensor address. It will then be recorded on tape along with its

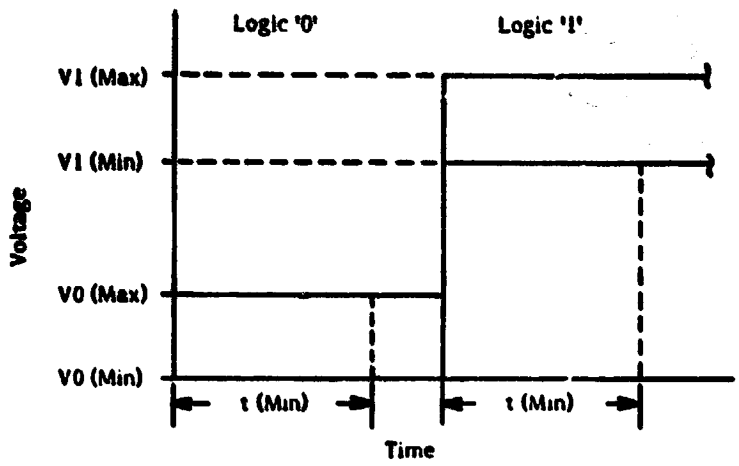


Figure 3-31 DISCRETE LOGIC LEVELS

identification and the time the data was taken. If the data to be stored is the status of a number of components, the identification code will then be unique to that group of components.

3.1.6 <u>Electrical Connections</u>. Two types of electrical connections, splices and receptical/plugs, will be required for the experimental equipment. The splices will be between the temperature sensors in the receiver tank and connections to the differential pressure transducer in the start basket. The temperature splices are shown as terminals FE13 through FE19 in Figure 3-26; the length of wire from each sensor to the splice shall be kept constant to keep the lead resistance between pairs of sensors constant. The sensor leads will be mounted to the pressure vessel or instrumentation tree a short distance from the sensor to provide for strain relief of the leads. The pressure vessel temperature sensor mountings will be of low thermal resistance to insure accurate measurement of pressure vessel temperatures. The leads of all the sensors shall be attached to the instrumentation tree at regular intervals to secure them against unnecessary strain. The leads will then be brought out through an instrumentation conduit, with sufficient slack to prevent strain during thermal cycling, and connected to the hermetically sealed receptacles. The second type consists of bayonet type receptacles, and plugs, including the hermetically sealed receptacles required to bring the instrumentation leads out of the hydrogen environment of the tank.

3.1.7 Power Requirements. Estimates of the component electrical power requirements for each phase of CFMF are given in Tables 3-XI and 3-XII, respectively. These estimates are based on previous experience or vendor data when available. Heater and valve estimates were not made because these are dependent on the particular application.

TABLE 3-XI CFMF ELECTRICAL POWER REQUIREMENTS, PHASE I

Component	Quantity	Voltage 400 Hz ac	Voltage dc	Unit Power at 293K milliwatts	Total Power watts
Temperature Sensors	63		28	30	2.40
Pressure Transducers	10		10	71	0.710
Quality Meters	3		28	750	2.250
Volumetric Flow	1		28	400	0.400
Accelerometer	1		28	8000	8.000
Heater	1	115		TBD	TBD
Solenoid Valves	20		28	TBD	TBD
Flow Control Valve	1	115		TBD	TBD

TABLE 3-XII CFMF ELECTRICAL POWER REQUIREMENTS, PHASE II

Component	Quantity	Voltage 400 Hz ac	Voltage dc	Unit Power at 293K milliwatts	Total Power watts
Temperature Sensors	52		28	30	2.40
Pressure Transducers	11		10	71	0.781
Quality Meters	5		28	750	3.750
Mass Gauge	1		28	4500	4.500
Volumetric Flow	1		28	400	0.400
Accelerometer	1		28	8000	8.000
Heater	1	115		TBD	TBD
Solenoid Valves	20		28	TBD	TBD
Flow Control Valves	2	115		TBD	TBD

3.2 Conceptual Design Analysis. The following paragraphs present the analyses conducted in support of the CFMF conceptual design. These analyses consist of: structural, weight and center of gravity (CG), thermal, fluid mechanic, and safety and reliability. The fluid mechanic analysis includes transfer line pressure drop, inlet manifold pressure/velocity distribution and the propellant acquisition system (i.e., start basket).

3.2.1 CFMF Structural Analysis. A structural analysis of the CFMF Phase I and Phase II Facility was conducted using the payload environments specified in Section 5.0 of Reference 19. An ultimate factor of safety of 2.5 against limit load conditions was used throughout the analysis in addition to the design requirements specified in Section 7.0 of Reference 19.

As part of the CFMF Facility, Beech Aircraft Corporation was directed to use the CFME supply tank and helium pressurant system. The structural analysis of the CFME was not conducted as part of this study effort.

The structural analysis of the Phase I and Phase II Facilities is contained in Paragraphs 3.2.1.1 and 3.2.1.2, respectively.

3.2.1.1 Phase I Facility Structural Analysis. The Phase I Facility General Arrangement is shown in Figure 3-1. The 0.36 scale receiver tank is designed for one mission and is supported by eight S-glass/epoxy struts that provide restraint against shuttle payload vibration and acceleration. The tank struts are mounted to an aluminum channel support structure that mounts directly to the Spacelab pallet hardpoints.

Receiver tank helium pressurant bottles are contained in a rack mounted directly to the Spacelab pallet below the receiver tank. The helium bottles are Kevlar-49 wound bottles with an aluminum liner. They are rated at 3000 psig operating pressure, 9000 psig burst pressure and 10,000 pressure cycles to operating pressure. These bottles are currently being Shuttle qualified and will be used as a part of the Manned Maneuvering Unit.

The 0.36 scale receiver tank is a cyclindrical tank with elliptical heads and two girth rings fabricated from 6061-T6 aluminum alloy. 6061-T6 aluminum alloy was chosen for its weldability and corrosion resistance properties.

The tank was sized using the Beech Conventional Tank Program. The user specifies fluid volume, pressure, density, tankage material and shape, the program then computes dimensions, areas and weights of the pressure vessel using standard stress equations. The program logic determines design information, such as membrane thickness and weight, plus weld and boss land weights for spherical and cylindrical tankage. The design stress used is the lower of the material ultimate stress divided by the factor of safety on ultimate or the material yield strength divided by the factor of safety on yield. The factor of safety on ultimate used is 1.50 and the factor of safety on yield used is 1.10. The results for the 0.36 scale pressure vessel are shown in Table 3-XIII.

TABLE 3-XIII 0.36 SCALE RECEIVER TANK SIZING

Pressure Vessel Type	Cylindrical - Elliptical Heads	
Pressure Vessel Material	6061-T6 Aluminum	
Fluid Volume	5.45 m^3	(192.4 ft^3)
Design Pressure	2.41 KPa	(35 psi)
Major/Minor Radii	1.38	
Total Inside Length	3.35 m	(132.079 in)
Head Wall Thickness	0.66 mm	(0.026 in)
Cylinder Wall Thickness	0.96 mm	(0.038 in)
Outside Radius	0.76 m	(30.038 in)
Cylindrical Length	2.25 m	(88.601 in)
Total Dry Weight	45.85 kg	(100.872 lb)

The receiver tank suspension system consists of eight S-glass epoxy tubular struts. An iterative procedure, shown by the flow chart in Figure 3-32, was used to size the struts. The system natural frequency is a function of the system spring constant. Since spring constant (K) is a function of cross section area (A), the system natural frequency (F_N) is also a function of A. By assuming A, F_N can be determined for the system and its response to the input power spectral density (PSD) can then be calculated. This allows a maximum load to be calculated and the strut checked to insure the tensile stress gives an acceptable margin of safety. Next, the compression stability is checked and, if found to be over or under designed, the cross-sectional area is decreased or increased correspondingly. Finally, the strut wall thickness is assessed to ensure an adequate wall thickness

for producibility. If the strut wall thickness was found inadequate for fabrication, the minimum wall thickness was selected and the calculation repeated. A review of current literature on strut fabrication indicates a wall thickness of approximatley 0.66 mm (0.026 in) is required to adequately fabricate struts.

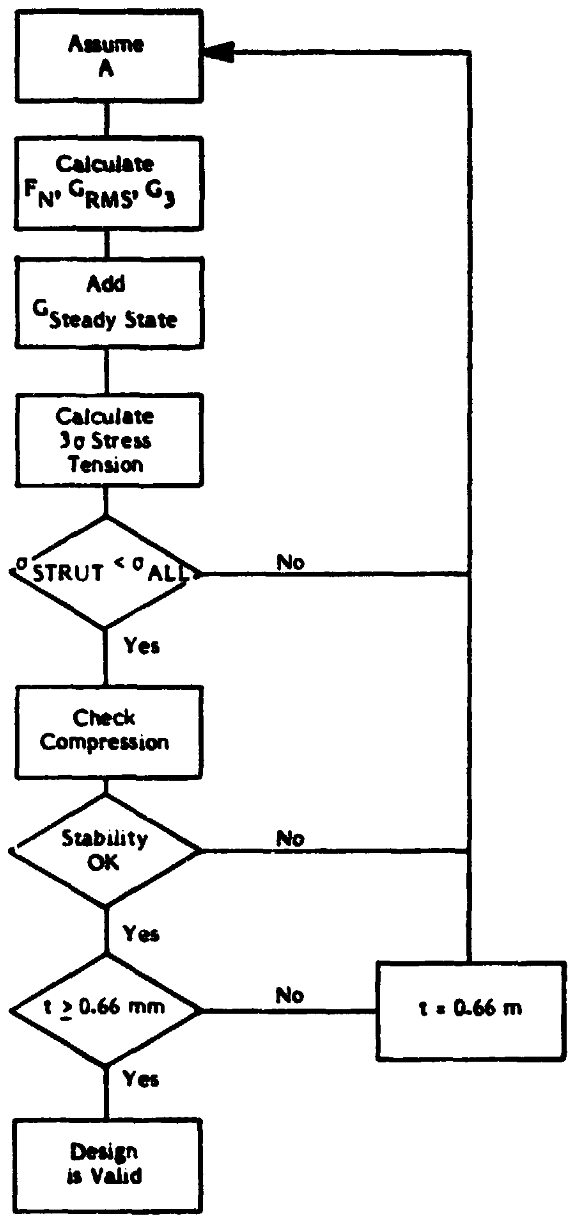


Figure 3-32 SUSPENSION SYSTEM ANALYSIS FLOW CHART

The equations used in the analysis flow chart are given below:

$$F_N = \frac{1}{2\pi}\left(\frac{Kg}{W}\right)^{1/2}$$

$$F_N = \frac{1}{2\pi}\left\{\frac{4AE\ COS^2\theta}{L\ W}\ g\right\}^{1/2}$$

$$G_{RMS} = \left\{\frac{\pi}{2} Q\, F_N\, S(F_N)\right\}^{1/2}$$

$$G_{3\sigma} = 3\, G_{RMS}$$

$$G_{SYS} = G_{3\sigma} + G_{SS}$$

$$F_{3\sigma} = G_{SYS}\, W$$

$$R_{3\sigma} = F_{3\sigma}/4\ COS\,\theta$$

$$\sigma_{3\sigma} = R_{3\sigma}/A$$

$$P_{CR} = \frac{\pi^2 E\, A}{(L/\rho_c)^2}$$

$$t \geq 0.66 \text{ mm}$$

where:

F_N	= System natural frequency - cycles/sec
K	= System spring constant - N/m (lb/in)
g	= 9.82 m/sec^2 (386.4 in/sec^2)
W	= System suspended weight - kg (lb)
A	= Strut cross-sectional area - m^2 (in^2)
E	= Strut modulus of elasticity - N/m^2 (7.5 x 10^6 psi)
θ	= Strut orientation angle above girth ring plane - deg
L	= Strut length - m (in)
G_{RMS}	= System response to input PSD - g's
$G_{3\sigma}$	= System 3σ response - g's
G_{SS}	= Steady state acceleration - g's
Q	= Amplification factor = 20.0

$S(F_N)$ = Value of PSD at F_N - g^2/Hz
$F_{Y3\sigma}$ = System 3σ load - N (lb)
$R_{3\sigma}$ = Strut 3σ load in axis of strut - N (lb)
$\sigma_{3\sigma}$ = Strut 3σ stress - N/m^2 (psi)
P_{CR} = Critical buckling load - N (lb)
ρ_c = Cross section radius of gyration - m (in)
t = Strut wall thickness - m (in)

The results of the support system analysis for the Phase I receiver tank are summarized below:

<u>Phase I</u>

Natural Frequency Data:

Axis	F_N (Hz)	G_{RMS} (g's)	G_{SS} (g's)	G_{SYS} (g's)
X	110	11.1	4.3	37.6
Y	110	11.1	1.4	34.7
Z	98	9.6	6.6	35.4

Top Struts:

L = 457.2 mm (18.0 in)
A = 78.7 mm^2 (0.122 in^2)
R_o = 38.1 mm (1.5 in)
t = 0.66 mm (0.026 in)

Bottom Struts:

L = 520.7 mm (20.5 in)
A = 64.5 mm^2 (0.100 in^2)
R_o = 31.0 mm (1.22 in)
t = 0.66 mm (0.026 in)

The iterative calculations performed for both the top and bottom struts resulted in strut thicknesses of less than the minimum and therefore the minimum thickness was used. After the struts were sized, a fatigue life analysis was conducted using the calculated system natural frequencies. Paragraph 5.1.3 of Reference 19 states that the exposure time of full level random vibration is 6 seconds per axis per flight; Reference 57 indicates that the MSFC is using the following times for fatigue analysis:

Liftoff (Steady State) = 9 sec

Liftoff (Random Vibration) = 50 sec + 20 sec/mission

Since the MSFC exposure times are more conservative, they were used throughout this analysis. The fatigue scatter factor of 4 was applied in estimating stress cycles except for random vibration which includes the fatigue scatter factor of 4. Miners cumulative damage theory (Reference 46) was used to assess fatigue life. Also, the 0.36 scale receiver tank will be used on only one mission. The fatigue cycles were calculated as follows using the above exposure times:

Liftoff:

$$n_L = F_N * 9 \text{ sec/flt} * 1 \text{ flt} * 4$$

Random Vibration:

$$n_r = F_N * (50 \text{ sec} + 20 \text{ sec/flt} * 1 \text{ flt})$$

The total number of fatigue cycles per axis is:

$$n_{\substack{tot \\ axis}} = n_l + n_r$$

Harris and Crede in Reference 47 state that sine-random equivalent damage can be predicted using a "g" level 2.2 times greater than the root mean square (RMS) random response ($g_{EQV} = 2.2\ g_{RMS}$). Using 2.2 block loads and a Gaussian (normal) distribution of fatigue cycles, the fatigue damage is less than 1.0. Fatigue life data (S/N Curves) for S-glass/epoxy are available in the literature (see Reference 48 for use in calculating fatigue damage).

The aluminum channel (76.2 x 38.1 mm or 3 x 1.5 in) structure that mounts directly to the Spacelab pallet was checked statically using the largest 3σ top strut axial load and standard beam stress equations and found to be acceptable.

3.2.1.2 Phase II Facility Structural Analysis The Phase II Facility General Arrangement is shown in Figure 3-13. The 0.165 scale receiver tank will be used for three missions. It is supported by eight S-glass/epoxy struts that provide restraint against shuttle payload vibration and acceleration. The tank/struts are mounted to an aluminum channel pallet that mounts directly to the Spacelab pallet hardpoints.

The 0.165 scale receiver tank heads have a 22.9 mm (0.9 in) straight section at the girth ring weld (reference Figure 3-16). This allows the head to be removed and rewelded twice, providing the tank with a two mission capability and one additional reweld.

The 0.165 scale tank was sized in the same manner as the 0.36 scale tank using the Beech Conventional Tank Program; the results are summarized in Table 3-XIV.

TABLE 3-XIV 0.165 SCALE RECEIVER TANK SIZING

Pressure Vessel Type	Cylindrical - Elliptical Heads	
Pressure Vessel Material	6061-T6 Aluminum	
Fluid Volume	0.52 m^3	(18.415 ft^3)
Design Pressure	2.41 KPa	(35 psia)
Major/Minor Radii	1.38	
Total Inside Length	1.540	(60.733 in)
Head Wall Thickness	0.635 mm	(0.025 in)
Cylinder Wall Thickness	0.635 mm	(0.025 in)
Outside Radius	0.348 m	(13.705 in)
Cylindrical Length	1.039 m	(40.907 in)
Total Dry Weight	7.28 Kg	(16.020 lb)

The receiver tank suspension system consists of eight S-glass/epoxy tubular struts. The design approach used is identical to the approach detailed for the Phase I facility receiver tank. The results of this analysis are summarized below:

Phase II

Natural Frequency:

Axis	F_N (Hz)	G_{RMS} (g's)	G_{SS} (g's)	G_{SYS} (g's)
X	220	26.3	4.3	83.2
Y	213	25.9	1.4	79.1
Z	305	31.0	6.6	99.6

Top Struts:

L = 609.6 mm (24.0 in)
A = 48.4 mm^2 (0.075 in^2)
R_o = 23.4 mm (0.920 in)
t = 0.66 mm (0.026 in)

Bottom Struts:

L = 304.8 mm (12.0 in)
A = 21.9 mm^2 (0.034 in^2)
R_o = 10.7 mm (0.420 in)
t = 0.66 mm (0.026 in)

The iterative calculations performed for both the top and bottom struts resulted in strut thicknesses of less than the minimum and therefore the minimum thickness was used. After the struts were sized a fatigue life analysis was conducted using the previously calculated system natural frequencies. The fatigue life factor of 4 was applied in estimating stress cycles. Three load blocks were used in the analysis (1σ, 2σ, 3σ) with the appropriate number of cycles based on a Gaussian (normal) distribution. This resulted in a fatigue damage of 1.0 using Miner's cumulative damage theory, for a three flight receiver tank usage.

The aluminum channel (76.2 x 38.1 mm (3 x 1.5 in)) structure that mounts directly to the Spacelab pallet was checked statically using the largest top strut 3σ load and standard beam stress equations and found to be acceptable.

3.2.2 <u>Weight and Center of Gravity Envelope</u>. The weight breakdown for the Phase I and Phase II facility, including the CFME and Spacelab pallet, is given in Table 3-XV. The location of the CFMF CG is shown in Figure 3-34 relative to a Spacelab pallet. The CFMF CG is shown in Figure 3-33, based on the total facility weight, including the Spacelab pallet weight shown in Table 3-XV. Also shown in Figure 3-33 is the single pallet nominal payload CG limits per Figure 4.1-14 of Reference 18. The Spacelab pallet weight was approximated from Table 3-I of Reference 18 for the five pallet configuration.

TABLE 3-XV CFMF WEIGHT BREAKDOWN

Component	Phase I Kg	Phase I (lb)	Phase II Kg	Phase II (lb)
Receiver Tank (Including Girth Rings)	50	(110)	7	(16)
Receiver Tank Support Frame	22	(49)	28	(61)
Internal Hardware	5	(10)	9	(20)
Top Support Struts	4	(8)	4.1	(9)
Bottom Support Struts	4	(8)	4	(8)
Helium Pressurant Bottles	68	(150)	68	(150)
Helium Bottle Support Frame	16	(36)	16	(36)
Lines	4	(8)	6	(13)
Instrumentation	25	(55)	35	(76)
Valves	34	(74)	38	(84)
Insulation	4	(8)	0.9	(2)
Miscellaneous (Heat Exchangers, Filters, Orifices)	11	(25)	11	(25)
CFMF	246	(541)	227	(500)
CFME	487	(1075)	487	(1075)
Spacelab Pallet	1091	(2400)	1091	(2400)
TOTAL	1824	(4016)	1805	(3975)

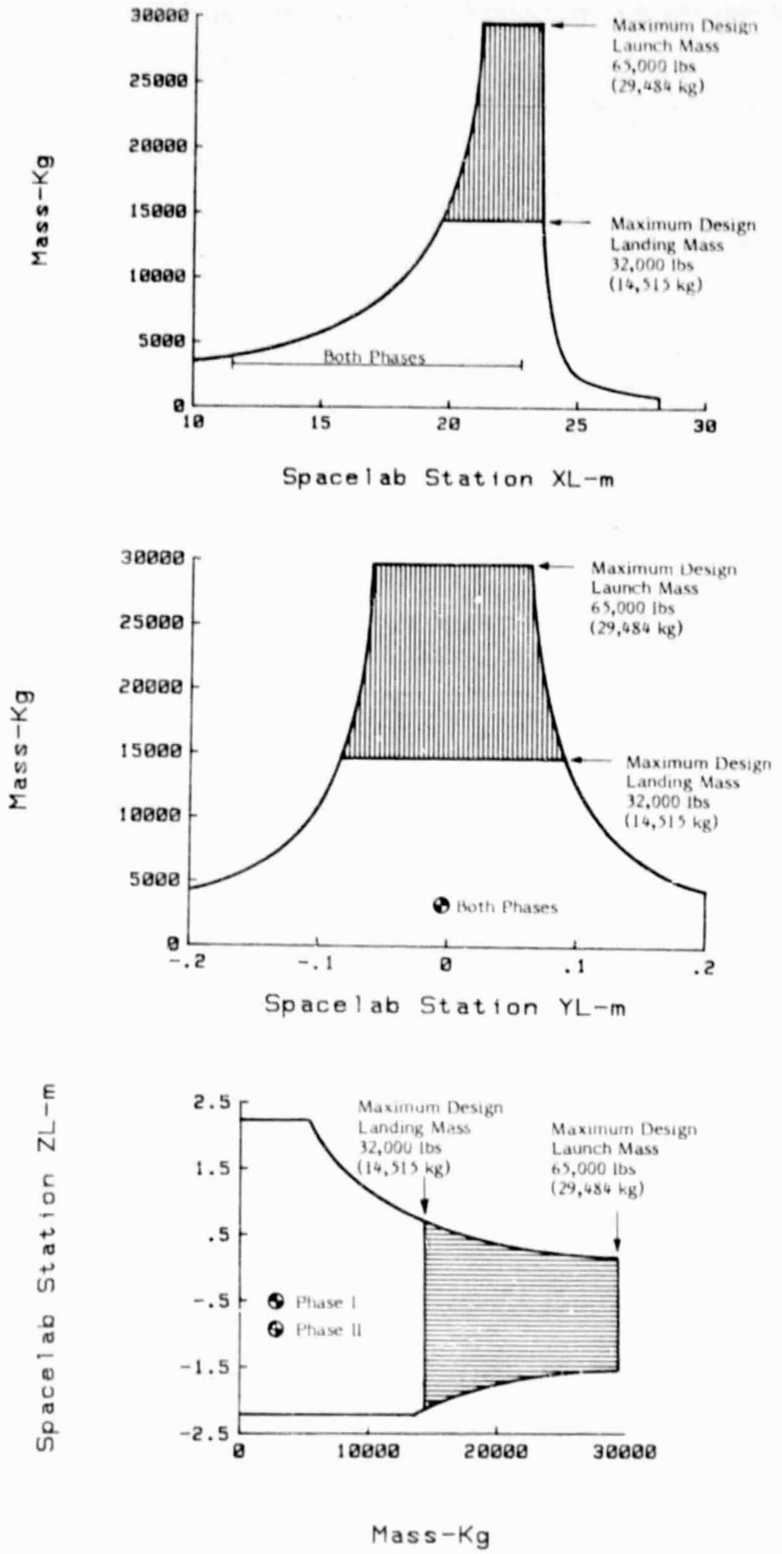


Figure 3-33 CFMF CENTER OF GRAVITY

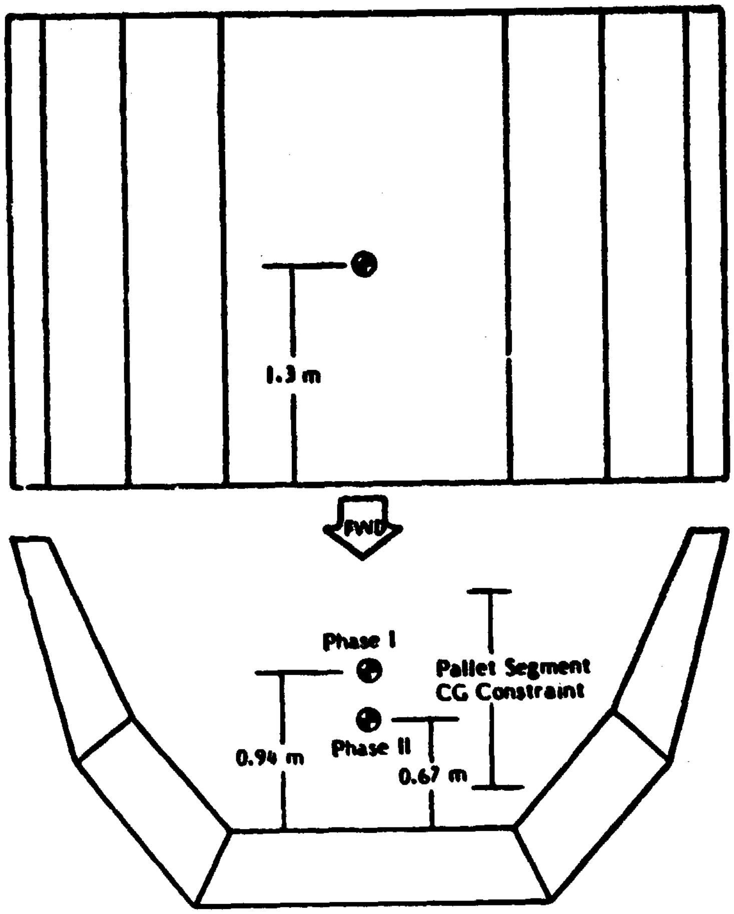


Figure 3-34 LOCATION OF CFMF CG ON A SPACELAB PALLET

3.2.3 Thermal Analysis. This paragraph presents the thermal analysis of the heat leak into the receiver tank and transfer line. These heat leaks were calculated at a worst-case cold condition of $20^{o}K$ ($36^{o}R$) and a time averaged external temperature of $308^{o}K$ ($555^{o}R$) representing the thermal environment during Shuttle thermal cycling.

Conduction from the external environment to the receiver tank pressure vessel is through the eight support struts, fluid lines and instrumentation wiring. This heat transfer is governed by Fourier's conduction equation (Equation 3-2) with conductivity given as a function of temperature.

$$\dot{Q} = \frac{A}{L} \int_{T_{pv}}^{T_{ext}} k(T)\, dT \qquad \text{(Equation 3-2)}$$

where:

A	= Cross-sectional area, m^2 (ft^2)
L	= Length, m (ft)
k	= Thermal conductivity as a function of temperature, w m/^oK (Btu/hr-ft-^oR)
T	= Temperature, ^oK (^oR)
T_{pv}	= Pressure vessel temperature, ^oK (^oR)
T_{ext}	= External environmental temperature, ^oK (^oR)

By integrating the nonlinear thermal conductivity over the temperature range T_{pv} to T_{ext}, conductive heat transfer through the support struts, instrumentation wiring and fluid was calculated.

The support struts are fabricated of S-glass/epoxy material. This material was used on the Beech Hydrogen Thermal Test Article (HTTA) and is currently being used on the Space Shuttle Power Reactant Storage Assembly (PRSA) Tanks. All fluid lines will be made from 304L stainless steel tubing. A summary of the line sizes selected for the facility is contained in Table 3-XVI. The instrumentation wiring, 150 leads, was assumed to be 0.127 mm (0.005 in) diameter copper wire.

TABLE 3-XVI CFMF LINE SIZE SUMMARY

Line	Outer Diameter mm	(in)	Wall Thickness mm	(in)
Inlet	9.5	(0.375)	0.508	(0.020)
Pressurization	6.4	(0.25)	0.508	(0.020)
Vent	12.7	(0.5)	0.711	(0.028)
Thermodynamic Vent	9.5	(0.375)	0.508	(0.020)
Fill/Drain Start Basket	9.5	(0.375)	0.508	(0.020)

The temperature dependent thermal conductivities for S-glass/epoxy, 304L stainless steel and copper are given in Figures 3-35 through 3-37. These curves were used, in conjunction with Equation 3-2, to determine the conductive heat leaks to the receiver tank.

The radiation heat transfer to the receiver tank was calculated using the following equation given in Reference 10:

$$\dot{q} = \dot{q}_{str} + \dot{q}_{He} \frac{K_n D_n^2 N_t N_n \quad (T_h - T_c)}{4000L} + \frac{\sigma (T_h^4 - T_c^4)}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1 \quad (N - 1)} \qquad \text{(Equation 3-3)}$$

where:

$\dot{q}$	= Heat flux, w/m^2
K_n	= Thermal conductivity of Dacron tuft fiber, 0.159 w/m ^oK
D_n	= Diameter of tuft fiber, 0.0178 mm
N_t	= 11065 Dacron tufts/m^2
N_n	= Number of Dacron fibers touching next layer = 8
L	= Insulation thickness, 25.4 mm
T_h	= Hot side temperature, 308^oK
T_c	= Cold side temperature, 20^oK
σ	= Stefan-Boltzman constant, 5.67×10^{-8} w/m^2 $^oK^4$
ϵ_1	= Emissivity of unflocked side of aluminized shield, 0.035
ϵ_2	= Emissivity of flocked side of aluminized shield, 0.043
N	= Total number of shields, 20
$\dot{q}_{str}$	= Heat flus of the insulation attachments and purging materials, w/m^2
$\dot{q}_{He}$	= Heat flux through the helium, w/m^2

The heat flux through Superfloc as a function of layer density is given in Figure 3-38. A heat flux of 0.57 w/m^2 (0.18 Btu/hr-ft^2) through 20 layers of Superfloc was used in calculating radiation heat transfer to the receiver tank. This heat flux was also used to calculate the heat transfered to the fluid transfer line during flow conditions. The heat fluxes through the insulation attachments and purging materials ($\dot{q}_{str}$) and the interstitial gas conduction ($\dot{q}_{He}$) was assumed to be zero. An experience factor of 1.5 was applied to radiation heat transfer in order to compensate for degradation from penetrations, layup, lap fasteners and environmental uncertainties.

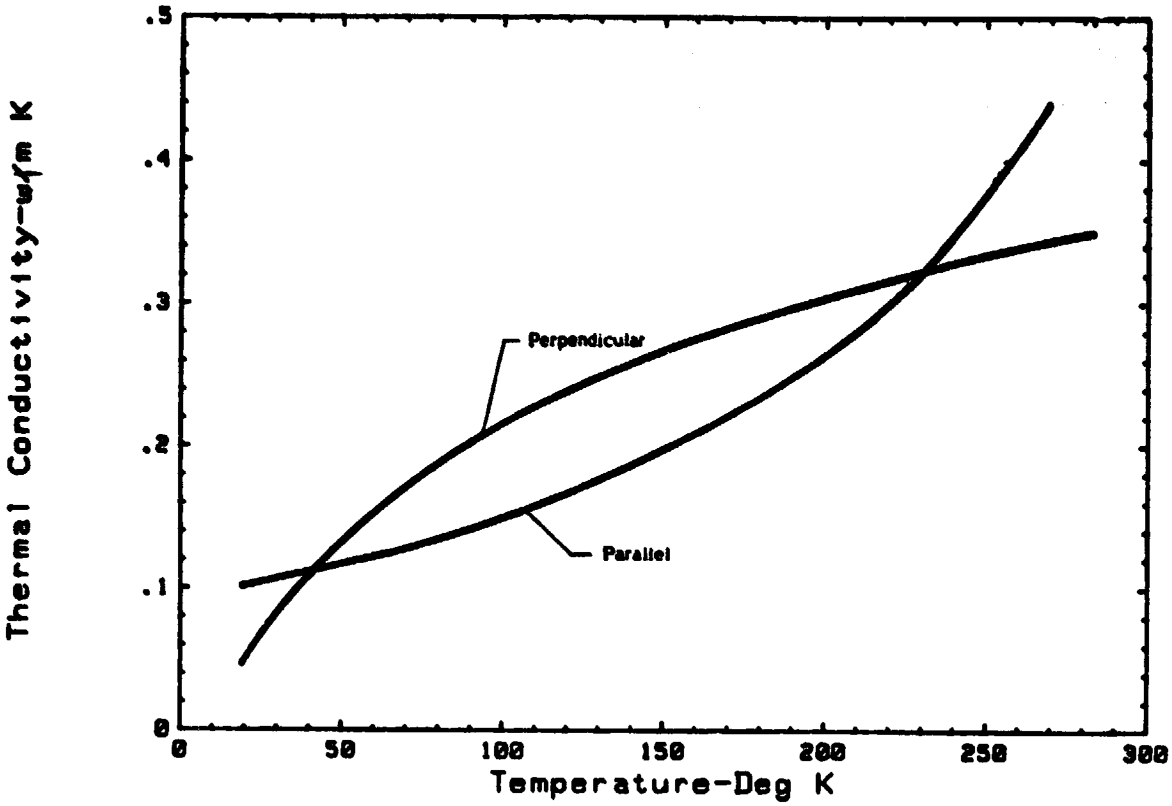


Figure 3-35 S-GLASS/EPOXY THERMAL CONDUCTIVITY
(Reference 58)

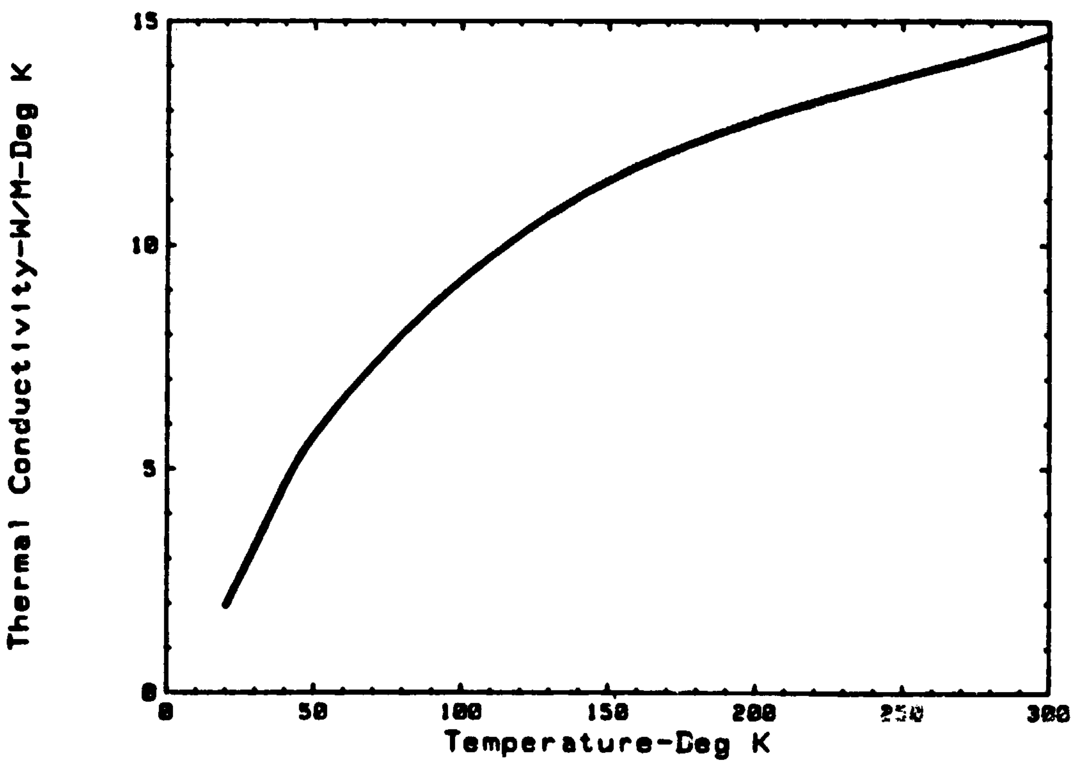


Figure 3-36 304 STAINLESS STEEL THERMAL CONDUCTIVITY
(Reference 59)

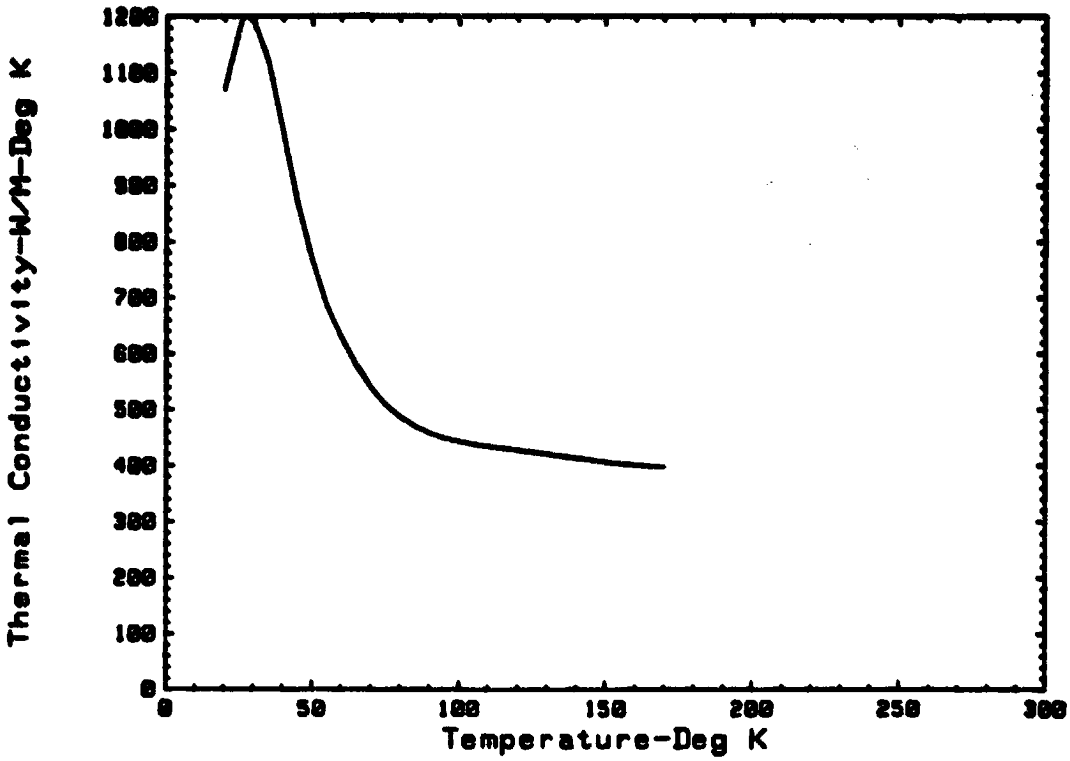


Figure 3-37 COPPER THERMAL CONDUCITIVITY
(Reference 59)

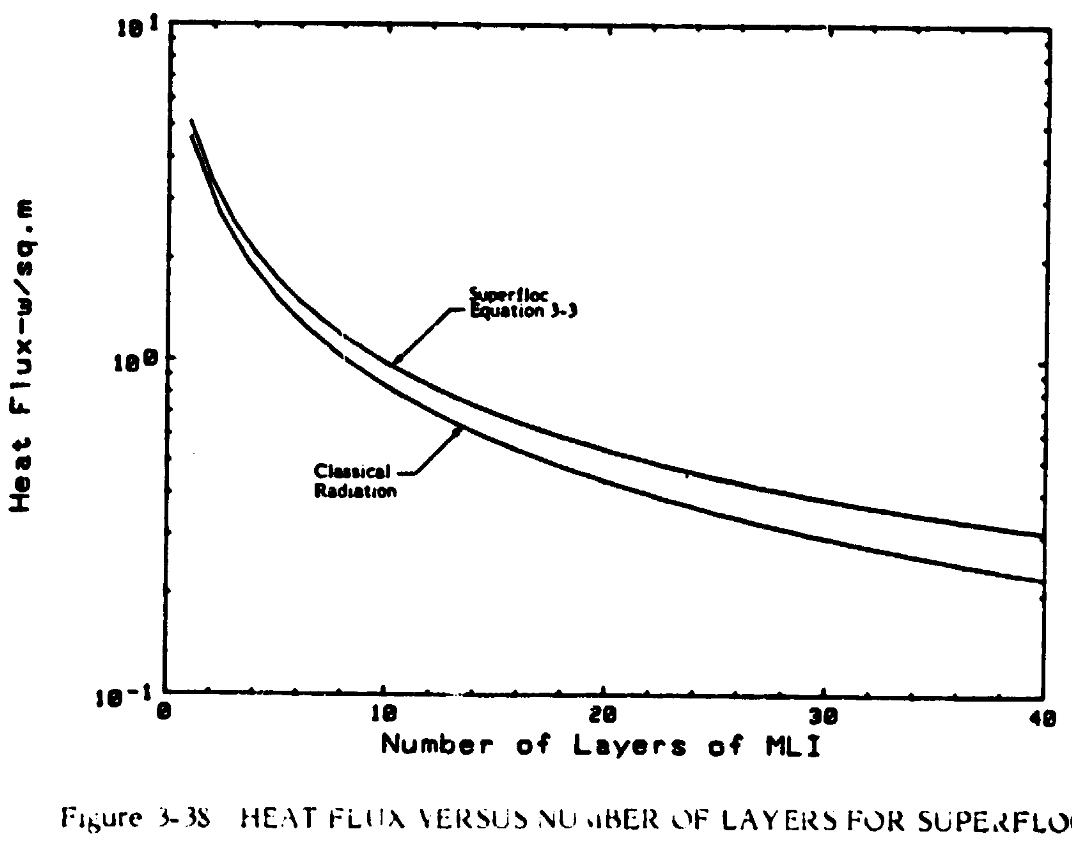


Figure 3-38 HEAT FLUX VERSUS NUMBER OF LAYERS FOR SUPERFLOC

A summary of the radiation and conduction heat transfer rates to the receiver tank is contained in Table 3-XVII. The heat leak to the transfer line, for worst case conditions, was calculated to be 9.3 w (31.7 Btu/hr).

TABLE 3-XVII SUMMARY OF RECEIVER TANK HEAT LEAKS

Mode/Component	Phase I		Phase II	
	Watt	Btu/hr	Watt	Btu/hr
Conduction:				
Support Struts	0.53	(1.8)	0.26	(0.9)
Instrumentation Wiring	0.50	(1.7)	0.50	(1.7)
Lines	0.97	(3.3)	1.52	(5.2)
Radiation:				
Insulation	14.2	(48.5)	3.0	(10.2)
TOTAL	16.2	(55.3)	5.3	(18.0)

3.2.4 Transfer Line Pressure Drop. To ensure that liquid enters the receiver tank, the minimum required LH_2 transfer pressure was calculated. This transfer pressure includes the frictional pressure drop through the line and components, and the pressure drop (i.e., level of subcooling) required to prevent two-phase flow formation from transfer line heat leak. Calculations based on the transfer line heat leak of 9.3 w (31.7 Btu/hr) indicated that, for the subcooled liquid, a temperature rise of $0.04^{o}K$ ($0.1^{o}R$) would result. This small change in temperature will not significantly increase the transfer pressure required.

The pressure drop analysis uses a one-dimensional incompressible flow model. This model assumes that the system is composed of connected line elements and components. Each section of line or component is treated as a separate entity and is represented by resistances expressed as pressure drops. The total transfer line pressure drop is then the summation of the individual line segment and component pressure drops. The general equation for pressure drop (Reference 49) is Darcy's equation. This equation, modified to make mass flow rate the independent variable, is given in Equation 3-4.

$$\Delta P = \frac{16}{C_b \pi^2 (2g_c)} \frac{fL}{D} \frac{\dot{m}^2}{\rho D^4}$$ (Equation 3-4)

where:

- ΔP = Pressure drop, Pa (psia)
- C_b = Conversion factor, 1 (144 in^2/ft^2)
- g_c = Gravitational constant, 1 $\frac{Kg\ m}{N\ sec^2}$ (32.17 $\frac{ft\text{-}lbm}{lbf\text{-}sec^2}$)
- f = Fanning friction factor
- L = Length, m (ft)
- D = Diameter, m (ft)
- $\dot{m}$ = Mass flow rate, Kg/sec (lb/sec)
- ρ = Density, Kg/m^3 (lb/ft^3)

The required friction factor for the straight line elements was computed utilizing the semi-empirical Colbrook-White equation given in Equation 3-5 (Reference 50). The lines are assumed to be drawn tubing with a relative surface roughness on the order of 1×10^{-4}.

$$\frac{1}{\sqrt{f}} = -2 \log_{10} \left(\frac{2.51}{Re\sqrt{f}} + \frac{\varepsilon}{3.7\ D}\right)$$ (Equation 3-5)

where:

- R_e = Reynolds number
- ε = Relative surface roughness

The pressure losses due to components (e.g., valves, bends, etc.) are also given by Equation 3-4 using the component loss coefficient K. In a flow system which has components separated by a sufficient distance to ensure they do not interact, the components are assigned loss coefficients independent of each other. This loss coefficient takes into account the immediate loss in the component and downstream losses due to the

flow field variations. The loss coefficient is generally given in terms of the flow coefficient C_v; the relationship between them is given by Equation 3-6 (Reference 49).

$$K = \frac{2.141 \times 10^{+9} d^4}{C_v^2} \qquad \text{(Equation 3-6)}$$

where:

d = Diameter (m)

To determine the component loss coefficients, vendor-supplied pressure drop data was used wherever possible. When this was not available, industry standard values for the size and type of component were used. The flow and loss coefficient data used in the transfer line pressure drop calculation is summarized in Table 3-XVIII. Figures 3-2 and 3-14 show the arrangement of components in the transfer line from which an estimate of the line segment length was made.

TABLE 3-XVIII CFMF PRESSURE DROP DATA

Component	C_v	K
Flow Control Valve	8.0	0.87
Solenoid Operated Valve	4.0	1.1
Check Valve	0.8	27.5
Quality Measurement Device	1.0	17.6

The frictional pressure drop through the transfer line, assuming a 22.7 gm/sec (0.05 lb/sec) flow rate of liquid hydrogen, was calculated to be 30 KPa (4.4 psia). This pressure drop indicates that helium pressure greater than 30 KPa (4.4 psia) is required in order to accomplish a liquid transfer.

3.2.5 Inlet Manifold. The analysis of the inlet manifold centered around maintaining nearly uniform pressure down the length of the manifold, thus assuring uniform flow

from each port. The work outlined in Reference 51 was used to predict the performance of the manifold. This analysis consists of a division of the fluid stream into paths by means of a manifold, which is accompanied by fluid pressure changes due to wall friction and changing fluid momentum. The friction produces a pressure reduction while deceleration of the portion of the fluid that undergoes a change of direction in flowing through a port tends to make the pressure rise. The calculations are based on a one-dimensional flow equation for tubes having constant cross-sectional area. The Phase I and Phase II CFMF manifolds are assumed to contain fifteen and eighteen 3.2 mm (0.125 in) ports, respectively. Since the spacing between the ports is relatively small, the approximation of a continuous homogeneous system is made. The result of the momentum balance and pressure drop calculation using the Fanning equation as given in Reference 51 is:

$$\frac{d^2U}{dy^2}\frac{dU}{dy} + U\frac{dU}{dy} + F_oU^{7/4} = 0 \qquad \text{(Equation 3-7)}$$

where:

$U \quad = u/u_o$

$F_o \quad = \dfrac{f_o}{2^{2.5}\,k^{1.5}\quad C}$

$y \quad = \dfrac{4\quad C}{D}\sqrt{2k\,x}$

u = Fluid velocity

f_o = Friction factor

k = Momentum adjustment for incomplete momentum recover (= 0.6)

C = Discharge coefficient for the side orifices

u_o = Initial fluid velocity

D = Tube diameter

α = Fraction of internal area of tube that is occupied by ports

x = Axial distance down manifold

Solving Equation 3-7 with the following boundary conditions at $x = 0$:

$$U = 1 \qquad \text{(Equation 3-8)}$$

$$\frac{dU}{dy} = -M_o \qquad \text{(Equation 3-9)}$$

where:

$$M_o = \left[\frac{g_c\,(p_o' - p_o)}{k\,\rho\,u_o^2}\right]^{1/2}$$

ρ = density

p_o' = Initial inflow pressure

p_o = Uniform pressure outside the ports

yields the fluid velocity distribution down the tube.

A summary of the CFMF inlet manifold conditions is given in Table 3-XIX. Using this information, M_o and F_o were evaluated and found to be 1.25 and 1.6, respectively. The results of numerically integrating Equation 3-7 are shown in Figure 3-39 with F_o = 1.9 for the Phase I manifold and F_o = 1.6 for the Phase II manifold with M_o = 1.25 for both manifolds. These results indicate that the flow variation down the manifolds should be less than three percent.

TABLE 3-XIX CFMF MANIFOLD OPERATING CONDITIONS

Parameter	Value		Phase II Value	
Mass Flow Rate	22.7 gm/sec	(0.05 lb/sec)	22.7 gm/sec	(0.05 lb/sec)
Tube Diameter	6.35 mm	(0.25 in)	6.35 mm	(0.25 in)
Friction Factor	0.015		0.015	
Discharge Coefficient	0.6		0.6	
Manifold Length	1.37 m	(50 in)	1.37 m	(50 in)
Fluid Density	70.8 Kg/m^3	(4.416 lb/ft^3)	70.8 Kg/m^3	(4.416 lb/ft^3)
Fluid Viscosity	1.3×10^{-5} Kg/m-sec	(0.9×10^{-5} lb/ft-sec)	1.3×10^{-5} Kg/m^2	(0.9×10^{-5} lb/ft-sec)
Port Diameter	31.8 mm	(0.125 in)	31.8 mm	(0.125 in)
Δp Across Port	6.9 KPa	(1 psia)	6.9 KPa	(1 psia)
Number of Ports	15		18	

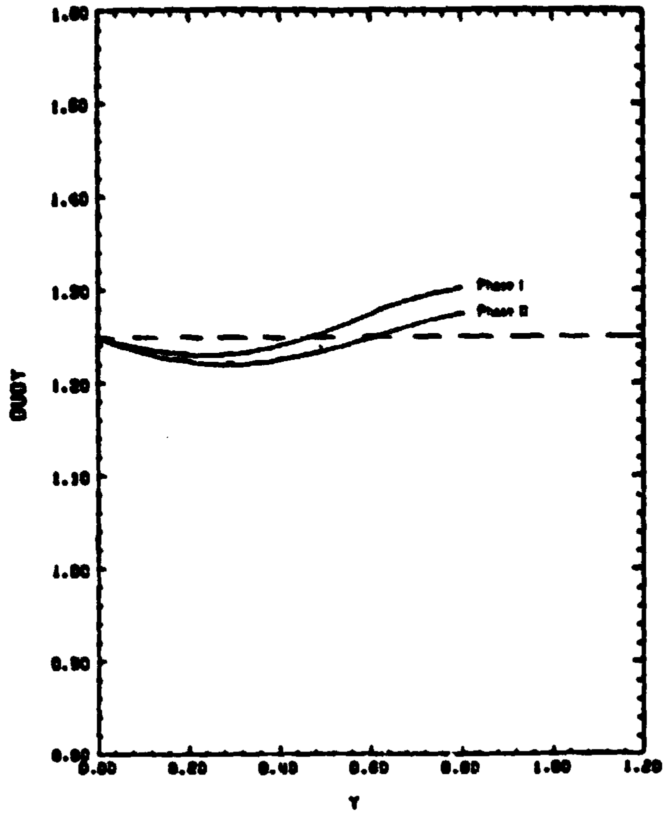


Figure 3-39 NONDIMENSIONAL FLOW VARIATION VERSUS DISTANCE

3.2.6 <u>Propellant Acquisition System</u>. The general configuration of the propellant acquisition system was discussed in Paragraph 3.1.2.3. This section describes the analysis and sizing of the start basket for the 0.165 scale tank. The operational requirements and design constraints were defined, then the start basket was sized to meet those requirements and constraints.

3.2.6.1 <u>Operational Requirements</u>. A typical duty cycle for a POTV start basket is:

<u>Initial Fill.</u> The basket is filled in through the outlet line while in orbit. Vapor may be trapped inside the basket during filling. This requires some method for collapsing trapped vapor bubbles.

<u>Coast</u>. During orbital coast, the liquid in the tank will tend to reposition itself away from the basket, toward the forward end of the tank. Portions, if not all, of the basket will be

surrounded by vapor. The basket will be subjected to heating which will cause evaporation at the screen surfaces and vapor inflow through the standpipe. The amount of vapor in the basket increases directly with the heating rate for a given coast period. The basket must be designed to accommodate the largest volume of vapor that can form during this period and to retain enough liquid to operate the engine during propellant settling.

Settling. Prior to engine restart, the tanks of a POTV would be pressurized and liquid flow from the start baskets would be initiated. The engine thrust causes the bulk of the liquid to settle toward the outlet end of the tank. As the liquid begins to settle, liquid will enter the start basket due to hydrostatic pressure. The settling time is a function of the quantity of liquid in the tank and the thrust level. For a POTV start basket, the thrust levels, and hence the settling times, are directly related to the start basket outflow rates. For the POTV model design, thrust is provided by the RCS thrusters, thus the g levels are independent of the start basket outflow rate.

Refill. The settled liquid refills the start basket by flowing through the main screen area while vapor flows out the standpipe. The driving pressure is the hydrostatic head between the top of the standpipe and the liquid level in the start basket. The refill rate for a given acceleration level and quantity of liquid in the tank is dependent upon the main and standpipe screen surface areas and flow resistances. This rate must be sufficient to refill the start basket during the shortest thrust period.

3.2.6.2 Design Constraints. The major design considerations for the design of a start basket were discussed in Paragraph 2.7.2.4. Table 3-IV (reproduced here) summarizes the specific design constraints for the 0.165 scale POTV tank start basket. The settling acceleration level, shown in Table 3-IV, is based on the -Y axis acceleration produced by the main RCS thrusters. It was assumed that disturbing accelerations in the +Y direction are limited to vernier thruster levels. This imposes a mission constraint to limit RCS thruster operation in the + Y-axis during start basket testing. If the disturbing accelerations were equal to the maximum settling acceleration, then it would not be possible to design the start basket to retain liquid during a disturbing acceleration and refill after settling. When the tank is less than 60 percent full, the start basket will not refill as the static head in the tank is not large enough to drive vapor from the standpipe with the low RCS acceleration levels. With the tank more than 60 percent full, preliminary calculations show the start basket should be refilled within one minute after settling is initiated (See Appendix III).

TABLE 3-IV 0.165 SCALE POTV TANK START BASKET DESIGN CONSTRAINTS

Tank:	0.165 Scale POTV Tank Overall Length = 1533.9 mm (60.39 in) Diameter = 695.7 mm (27.39 in) Elliptical Heads With Major/Minor Axis Ratio of 1.38
Fluid:	LH_2 at 20°K (36°R)
Flowrate:	Propellant Outflow Rate = 0.02 kg/sec (0.05 lbm/sec)
Acceleration:	Maximum Settling Acceleration = 0.22 m/s^2 (0.7 ft/sec^2) along -Y-axis due to RCS main thrusters Maximum Disturbing Acceleration = 0.002 m/s^2 (0.007 ft/sec^2) along +Y-axis due to RCS vernier thrusters
Duration of Zero g:	Liquid will be retained in start basket for ten hours maximum.

3.2.6.3 Main Screen Sizing. The pore size of the main screens is based on retaining liquid in the basket during settling and disturbing accelerations. That is, the penetration pressure of the screen must exceed the maximum static head of liquid in the basket. The governing relationship is:

$$\Delta p_B \geq \frac{\rho_L\, g\, x}{g_c} \qquad \text{(Equation 3-10)}$$

where:

Δp_B = Screen penetration pressure
ρ_L = Liquid density
g = Acceleration
x = Liquid height in the direction of acceleration

The penetration pressure is given by:

$$\Delta p_B = \frac{K\sigma}{D_{Bp}\,(SF)} \qquad \text{(Equation 3-11)}$$

where:

σ = Liquid surface tension
D_{Bp} = Absolute screen pore size
K = Empirical constant to account for screen geometry (K = 2.7 for Dutc weave; 3.0 for square weave)
(SF) = Safety factor (equal to 1.5)

Combining Equations 3-10 and 3-11, the maximum pore size to retain liquid is:

$$D_{Bp} \leq \frac{K \sigma g_c}{\rho_L g x (SF)} \quad \text{(Equation 3-12)}$$

The calculations for maximum pore size are summarized in Table 3-XX. The length, x, used to calculate the maximum pore size for the main screen is the diameter of the start basket since the maximum acceleration is perpendicular to the axis of the tank.

TABLE 3-XX MAIN SCREEN SIZING CALCULATION

Variable	Value
g	0.40 m/sec^2 (1.3 ft/sec^2)
ρ_L	70.5 Kg/m^3 (4.4 lb/ft^3)
σ	2.25 dyne/cm (1.12 x 10^{-5} lb/in)
x	406.4 mm (16 in)
K	2.7
SF	1.5
D_{Bpmax}	311 μm

3.2.6.4 Standpipe Sizing. The maximum pore size of the standpipe screen is determined by the requirement that the standpipe must retain liquid during adverse accelerations (accelerations opposite to the settling direction). The column of liquid which must be retained is equal to the length of the standpipe plus the height of the start

basket. The minimum pore size is set by the refill requirements. To permit complete refilling of the start basket, the gas penetration pressure of the standpipe screen must be less than the static head of a column of liquid equal to the length of the standpipe subjected to the settling acceleration. This pore size is determined by Equation 3-13.

$$D_{Bp} \leq \frac{K \sigma g_c (g_s - g_a)}{\rho_L g_s g_a a (SF)} \qquad \text{(Equation 3-13)}$$

where:

g_s = Settling acceleration
g_a = Adverse acceleration
a = Height of start basket

The sizing calculations for the standpipe are shown in Table 3-XXI:

TABLE 3-XXI STANDPIPE SCREEN SIZING CALCULATION

Variable	Value
g_a	0.0021 m/s^2 (0.007 f/s^2) (vernier thrusters)
g_s	0.22 m/s^2 (0.7 f/s^2)
ρ_L	70.5 Kg/m^3 (4.4 lb/ft^3)
σ	2.25 dyne/cm (1.34 (10^{-4}) lb/ft)
a	76.2 mm (0.25 ft)
K	2.7
SF	1.5
D_{Bpmax}	304367 μm

This calculation demonstrates the adverse accelerations are so low that there are virtually no retention requirements for the standpipe.

The minimum length of the standpipe required for a given screen pore size is:

$$L = \frac{K \sigma g_c}{\rho_L g_s D_{Bp}} = \frac{1153}{D_{Bp}} \qquad \text{(Equation 3-14)}$$

where D_{Bp} is less than D_{Bpmax}. To minimize the length of the standpipe, the coarsest screen available with good wicking properties should be used. Using 10 x 52 mesh Dutch plain weave, with a pore size of 325 μm, the minimum standpipe length is:

$$L_{min} = 1081 \text{ mm } (3.55 \text{ ft})$$

Square weave screens have larger pore sizes and would permit a shorter standpipe. However, square weave screen by itself does not wick and will require modification, such as a perforated backing plate to promote wicking.

A standpipe fabricated from dutch weave screen, whose coarsest mesh has a bubble point diameter of 325 microns will require a standpipe height of 1081 mm (3.55 ft). Because of the potential design problem of wicking along the standpipe length, this configuration and several alternatives were examined for accomplishing start basket test objectives.

1. Use a 1081 mm (3.55 ft) standpipe with the supporting structure required for its length. To conduct a refilling test, approximately 80 percent of liquid must be present in the tank to cover the standpipe when the tank contents are settled. For the low-g liquid retention performance, the basket should be surrounded by vapor, thus less than 20 percent liquid should exist in the tank and be positioned in the forward bulkhead. This may be accomplished by conducting the refilling test at 80 percent full, draining to 20 percent or less, waiting for sufficient time without disturbances to position the liquid in the forward end of the tank and then conducting the liquid retention testing.

2. Use a 152 mm (6 in), 325 micron dutch weave screen standpipe to minimize structural problems and facilitate wicking along the standpipe. This approach would eliminate the possibility of refill testing because of insufficient hydrostatic head to force vapor out of the standpipe. It would, however, provide a more

realistic configuration with regard to wicking distance requirements relative to the POTV. Structural and design considerations would also be more in line with the anticipated POTV configuration.

3. Use a 502.9 mm (1.65 ft) standpipe with a 24 mesh square weave screen (700 microns) backed by a perforated plate to facilitate wicking while maintaining low retention capability. This approach has the potential of providing refill capability and permits all experiment objectives to be achieved. However, it creates a developmental problem with regard to the fabrication and performance of the square weave screen/perforated plate wicking barrier.

3.2.6.5 Start Basket Volume. The liquid volume in the start basket must provide for the following:

1. Engine chilldown
2. Settling
3. Evaporative losses during zero gravity
4. Channel volume
5. Residuals
6. Standpipe volume

Engine Chilldown. In a POTV there would be a liquid volume required for engine chilldown prior to ignition. Since this volume is determined by the particular application, no attempt was made to include a "chilldown" volume in the CFMF start basket.

Settling. The settling time was calculated as five times the free fall time. This calculation used the RCS acceleration of 0.22 m/sec^2 (0.72 ft/sec^2) and the distance from the flat liquid interface to the opposite end of the tank. For complete refilling the end of the standpipe must be covered by liquid. For the 1081 mm (3.55 ft) standpipe this means that the tank is roughly 60 percent full and the settling distance is 0.61 m (2.0 ft). Using Equation 3-15, a settling time of 11.8 seconds was calculated.

$$t_{ss} = 5\sqrt{2\ H/g_s} \qquad \text{(Equation 3-15)}$$

where:

H = Free fall height, m (ft)

g_s = Settling acceleration, m/sec^2 (ft/sec^2)

The required volume for settling is given by Equation 3-16:

$$V_{ss} = \frac{\dot{m}_{out}\, t_{ss}}{\rho_L} \qquad \text{(Equation 3-16)}$$

where:

$\dot{m}_{out}$ = Outflow rate, Kg/sec (lb/sec)
ρ_L = Liquid density, Kg/m^3 (lb/ft^3)

The outflow rate from the basket is arbitrary; however, based on refill calculations as discussed in Appendix III, the maximum outflow rate at which refill will occur for the proposed start basket is 9.1 g/sec (0.02 lbs/sec). Using an outflow rate of 9.1 g/sec (0.02 lbs/sec) and a tank fill level of 60 percent, the settling volume is:

$$V = 1.52 \times 10^{-3}\ m^3\ (0.054\ ft^3)$$

<u>Evaporative Losses</u>. Evaporative losses from the start basket during zero g are due to heat transfer into the basket. This heat transfer is a combination of three components: heat transfer across the tank wall incident on the elliptical surface, heat transfer to the conical surface and standpipe by convection and heat transfer by conduction through supports, lines and penetrations. The total heating rate during zero-g coast was estimated to be 0.28 w (0.96 Btu/hr). Contributions from the elliptical surface, conical surface/standpipe, and conduction heat leak components are 0.095 w (0.33 Btu/hr), 0.182 w (0.62 Btu/hr) and 0.003 w (0.01 Btu/hr), respectively.

The volume of liquid evaporated due to this heating is given by:

$$V_{TL} = \frac{\dot{Q}_T\ \Delta t}{\rho_L\ \lambda} \qquad \text{(Equation 3-17)}$$

where:

$\dot{Q}$ = Heat rate into the start basket, w (Btu/hr)
Δt = Time between settled periods, hr
ρ_L = Liquid density, g/cm^3 (lb/ft^3)
λ = Heat of vaporization, J/Kg (Btu/lb)

If a 10-hour coast period is assumed, the evaporative loss will be:

$$V = 3.11 \times 10^{-4}\ m^3\ (0.011\ ft^3)$$

Channel Volume. Channels are designed for supplying vapor-free liquid to engines regardless of the vapor/liquid orientation in the basket prior to engine restart. They must therefore extend into the basket volume and maintain enough liquid in contact with the screen surfaces to prevent vapor ingestion into the channels. The channels were sized based on maintaining similarity between this model design and that used for the POTV in Reference 43. The POTV design had channels that extended to the intersection of the conical and elliptical section of the basket from the outlet. This was maintained in the 0.165 scale model. Channel dimensions of 50.8 mm x 127 mm (2 in x 5 in) for the POTV were scaled to 9.5 mm x 25.4 mm (3/8 in x 1.0 in) (approximate linear scaling) in the 0.165 scale model. The resulting channel volume is:

$$V = 2.27 \times 10^{-4}\ m^3\ (0.008\ ft^3)$$

Residuals. The residual volume is to ensure that liquid is in contact with the channel screens at the start of outflow. The area of screen/liquid contact, through which liquid enters the channels, must be sufficient to prevent channel screen breakdown and vapor ingestion.

For the residual calculation it was assumed that all the liquid was located in the upper portion of the start basket. This is the liquid orientation for which the liquid volume retained in the basket when the channel screens breakdown is a maximum.

Using the flow resistance characteristics of the 325 x 2300 channel screen and an outflow rate of 9.1 g/sec (0.02 lbs/sec), the liquid volume required to ensure vapor-free outflow is:

$$V = 1.76 \times 10^{-3}\ m^3\ (0.062\ ft^3)$$

Standpipe Volume. The standpipe volume depends upon which alternative standpipe design is used. Assuming the third alternative (1081 mm (3.55 ft)) and a diameter of 25.4 mm (1.0 in), the standpipe volume is:

$$V = 6.59 \times 10^{-4}\ m^3\ (0.023\ ft^3)$$

Start Basket Volume Summary. Table 3-XXII summarizes the results of the start basket volume calculations.

TABLE 3-XXII START BASKET VOLUME CALCULATION SUMMARY

Component	Volume	
Settling	1.52×10^{-3} m^3	(0.054 ft^3)
Evaporative Losses	3.11×10^{-4} m^3	(0.011 ft^3)
Channel Volume	2.27×10^{-4} m^3	(0.008 ft^3)
Residuals	1.76×10^{-3} m^3	(0.062 ft^3)
Standpipe Volume	6.59×10^{-4} m^3	(0.023 ft^3)
Margin (25 percent)	1.56×10^{-3} m^3	(0.055 ft^3)
TOTAL	0.0060 m^3	(0.213 ft^3)

3.2.6.6 Start Basket Geometry. A schematic of start basket geometry is shown in Figure 3-21. The dimensions of the start basket were calculated to correspond to the volumes given in Table 3-XXII. They are:

r = 223.3 mm (8.79 in)
h = 61.7 mm (2.43 in)
c = 23.4 mm (0.92 in)
L = 502.9 mm (19.8 in)

Based on the constraint of Equation 3-12, the coarsest wicking screen possible, 10 x 52, would be selected (D_{BP} = 325 μ m) for standpipe alternatives 1 and 2. The next coarsest screen wicking available, 12 x 64, (D_{BP} = 295 μ m), would be used for the main screen. Two layers of this screen are used, backed with perforated plate (51 percent open area, 9.5 mm (3/8 in) holes on 12.7 mm (1/2 in) centers). For the channel screen, 325 x 2300 mesh was chosen to be representation of a POTV configuration, allowing a reasonably high mass flow per unit area and good screen retention capability.

For standpipe alternative 3, the constraints of Equations 3-13 and 3-14 must be satisfied. The standpipe screen would be a 24 mesh square weave (700 μm) microns corresponding to a standpipe height of 502.9 mm (1.65 ft).

3.2.7 Safety and Reliability Analyses. This paragraph analyzes each phase of the CFMF and identifies inherent hazards and system limitations. These analyses comply with the NASA payload safety requirements. As the design matures, additional analyses will be added, refined and expanded.

The results of the Fault Hazard Analysis, including the standard Failure Modes and Effect Analysis, and the System Safety Fault Hazard Analysis data as defined by NHB 1700.1 (V3), System Safety (Reference 52), are presented in Appendix I.

Information presented in the "Component Failure Rate" column was derived from Reference 53. As particular valves, sensors, meters and transducers are selected during the detailed design, the manufacturer's and/or test data will be utilized to update the failure rate data.

"Electrical failure" has been listed several times in the "Factors That May Cause Secondary Component Failure" Column and "Upstream Components or Inputs That May Cause Sequential Failures" Column. These electrical failures may range from complete electrical failure of the experiment to the component failing to receive a signal from the DACS.

Nucleonic fluid gauging was selected for the conceptual design. The radiation source and detector unit will be mounted externally to the receiver tank. Krypton 85 will be used in the aluminum alloy source tubing. Approximately 6 millicuries of Kr-85 (which is the equivalent to 300 millicuries total gamma ray strength) will be the radiation source. The tubing will have sufficient density/thickness to stop beta particles and will have negligible Bremsstrahlung output.

While sufficient information is not available for a hazard analysis on the Mass Gauging System, the "Payload Safety Guidelines" of JSC Handbook 11123, Section 3.14 (Reference 54), will be followed, as well as information contained in GE Study 72SD4201, "Manned Space Flight Nuclear System Safety" (Reference 55). The JCS Space Shuttle Program Office will be contacted and approval received during the Preliminary Design Phase of the project.

The conclusions from this analysis show that no single point failure of this system will cause an unsafe condition on the launch pad or in orbit; however, several single point failures will terminate the experiment. Future analysis will require an updating of the Component Failure Rate data and their Criticality Factors.

3.3 <u>Facility Support Requirements</u>. This paragraph defines the ground and on-orbit facility support requirements. Ground support equipment required to service the CFMF and the Payload Specialist on-orbit support requirements are defined in Paragraphs 3.3.1 and 3.3.2, respectively.

3.3.1 <u>Ground Support Equipment (GSE)</u>. The GSE required to service the CFMF before launch includes a cryogenic hydrogen loading system to fill the supply tank, a gaseous helium loading system for charging facility helium bottles, and mechanical equipment for handling and lifting. This paragraph provides a conceptual discussion of the GSE required for the CFMF.

3.3.1.1 <u>Cryogenic Servicing Equipment</u>. The Beech-built Fuel Cell Servicing System (FCSS) is currently used to load the Space Shuttle Power Reactant Storage Assembly (PRSA) tanks with supercritical hydrogen and oxygen. The FCSS can be used to fill the CFMF supply tank with LH_2 through the midbody umbilical, shown schematically in Figure 3-41; however, changes in the operating procedure will be required to fill the supply tank with low pressure (12 N/cm^2 (18 psia)) saturated liquid. Modifications to the system to provide a fifth LH_2 fill line would be required or, for an unmodified FCSS, a tee and shutoff valves would have to be installed in a LH_2 PRSA fill line inside of the Space Shuttle.

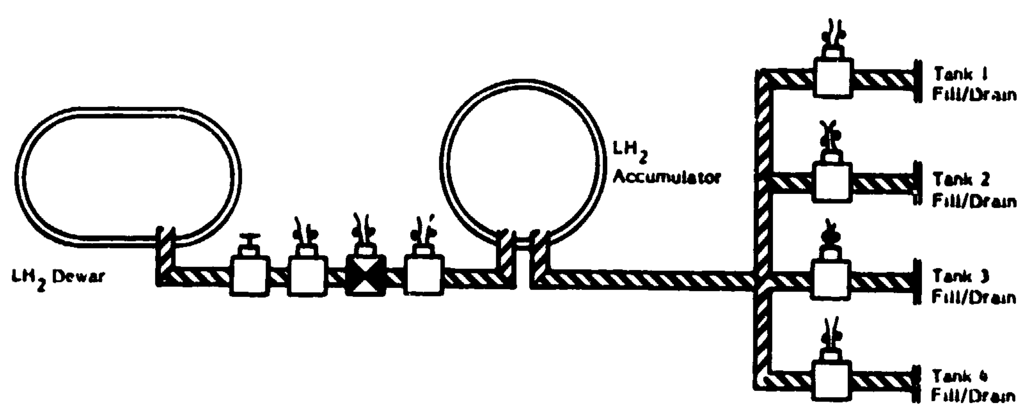


Figure 3-40 FCSS SCHEMATIC

If fewer than four hydrogen reactant tanks are installed in the Orbiter, the CFMF supply tank could be connected to one of the four fill/drain lines on the FCSS. If four reactant tanks are installed, it would be necessary to tee into a reactant tank fill line on the Orbiter (as shown in Figure 3-41) to avoid modifying the FCSS. Venting the supply tank during servicing would be through the FCSS vent system; however, a fifth vent line would be needed. Provision for this vent is included in the FCSS design; however, the line has not currently been installed. After fill, when the midbody umbilical is disconnected, venting is through the T-O umbilical.

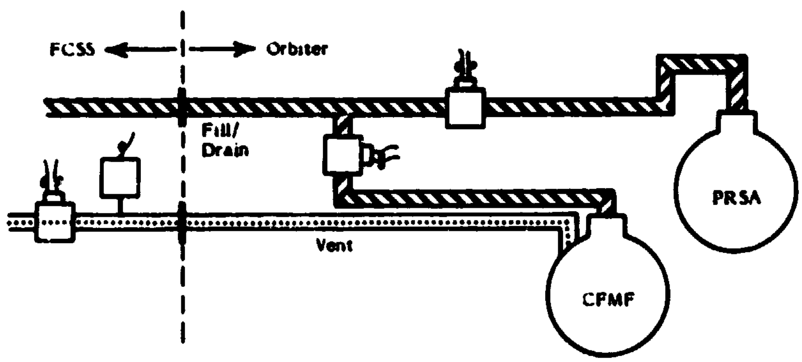


Figure 3-41 DETAIL OF ALTERNATE CFMF FILL CONNECTION

The basic procedure for loading the CFMF supply tank after the reactant supply tanks have been loaded is as follows:

1. Reactant supply tanks are isolated from the FCSS.

2. The FCSS is depressurized.

3. If fewer than four reactant tanks are in the Orbiter, the supply tank is filled directly through the appropriate fill/drain line. If, however, the CFMF supply tank is teed into a reactant tank fill line, then the valves shown in Figure 3-42 must be properly positioned to fill the supply tank.

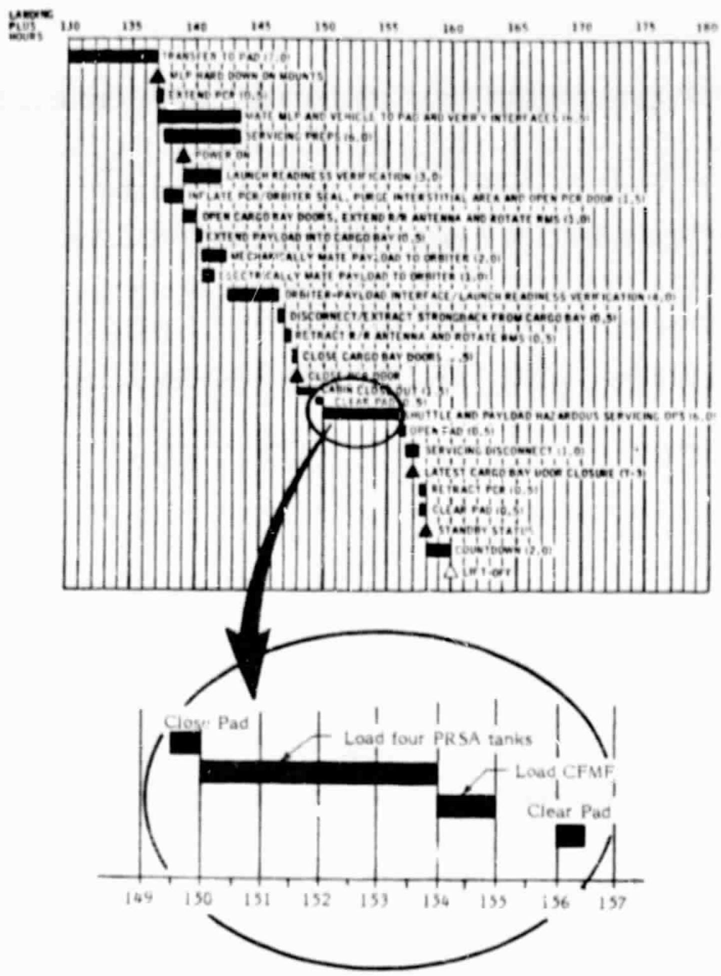


Figure 3-42 CFME LOADING SCHEDULE

4. Filling is terminated when the vent line liquid level sensor detects liquid in the line.

5. Fill lines are purged.

Based on experience with filling the PRSA tanks, the time required to fill the CFMF supply tank should be less than 30 minutes. As shown in Figure 3-43, this is compatible with the Orbiter launch preparation schedule.

A failure analysis of the FCSS (Reference 56) concluded that the hazards of operating the FCSS are no greater than those of other similar systems operated at KSC. Use of the FCSS for loading the CFMF supply tank should not result in additional hazards during cryogen servicing.

3.3.1.2 Gaseous Helium Servicing Equipment. The gaseous helium bottles for the CFMF supply and receiver tanks will be charged in the Operations and Control (O&C) Building prior to pallet-to-Shuttle integration. This system includes all the required valves, flex lines and regulators necessary to fill the bottles (maximum pressure 2162 N/cm^2 (3135 psia) at 29^oC (85^oF)).

3.3.1.3 Handling Equipment. Fixtures for handling the supply tank prior to installation on the pallet will have been designed as part of the CFME design effort. Similar fixtures would be needed for the receiver tank and its associated hardware.

3.3.2 Payload Specialist. The Payload Specialist's involvement in monitoring the facility is to be minimized; however, some interaction is required. The interface between the facility and the mission Payload Specialist is through the Aft Flight Deck (AFD). He will be responsible for the requests made by the facility DACS for RCS thruster firing, as well as honoring requests for low acceleration coast periods. In addition, the Payload Specialist will have the capability to monitor the facility's progress through its preprogrammed sequence. This capability is necessary to provide the Payload Specialist with any information required in the event an experiment abort is required.

3.4 Mission Constraints. This paragraph defines the constraints imposed by the CFMF during its operating period on the Space Shuttle mission. These constraints can be broken down into three major categories: (1) thermal constraints, (2) acceleration requirements and (3) mission scheduling.

3.4.1 Thermal. The maximum and minimum pallet surface temperatures are dependent on the mission profile. A maximum pallet surface temperature of 393^oK (708^oR) and a minimum temperature of 123^oK (222^oR) were used for analysis purposes. Based on this preliminary analysis, it was concluded that the CFMF will not impose thermal constraints on the Space Shuttle mission. During the detailed design of CFMF, however, it will be necessary to ensure that temperature limits for valves and quality gauging system within the facility are not exceeded.

3.4.2 Acceleration. The constraints imposed by acceleration requirements are based on the need for low acceleration coast and utilization of the RCS primary thrusters. The low acceleration coast will be required to simulate POTV operations. Assessment of the tapered vent tube and internal heat exchanger/fan operations during Phase II, Mission Two, and the thermodynamic vent system operation and start basket testing during Phase II, Mission Three, will require a low acceleration environment.

In Phase II, Mission Two, the reactant control system primary thrusters will be utilized during venting and receiver tank draining. Once the receiver tank start basket has been filled (Mission Three), the -Y RCS primary thrusters may not be fired; firing of the RCS engines during this period will result in start basket breakdown. The reactant control system +Y primary thrusters will be required during start basket refill and tank draining processes. Cycles of RCS thruster firing and low acceleration coast periods will be required during start basket testing.

3.4.3 Mission Scheduling. The CFMF (Missions Two and Three) must not to be flown with other experiments which require large quantities of RCS propellant, special accelerations, directional requirements or solar positioning. The second and third missions require approximately 680 Kg (1500 lbs) and 862 Kg (1900 lbs) of RCS propellant respectively. These propellant requirements are nearly half of the total RCS propellant available for payload support and, therefore, will influence mission availability and scheduling.

3.5 Experimental Test Plan. To meet the mission objectives, an Experimental Test Plan for the CFMF was developed. This Test Plan defines the ground test requirements, launch procedure and on-orbit sequence of operations for each of the three missions.

3.5.1 Phase I Test Phase. The following paragraphs describe the Experimental Test Plan for Phase I.

3.5.1.1 Ground Test Requirements. The ground test requirements consist of those test items to be performed at KSC following integration of the CFMF with the Spacelab pallet. These requirements assume that component and system checkout was accomplished prior to shipping.

The ground test requirements for the CFMF are:

1. Continuity check of all electrical circuits.
2. Verification of supply tank vacuum integrity.
3. Leak check with ambient temperature helium.
4. Check operation of fill valves with low pressure ambient helium.
5. Instrumentation checkout.
6. Recorder and DACS checkout - check manual on, off and abort capability.
7. Check C&W signal generation.

These tests will be performed prior to pallet-to-Shuttle integration, Level I.

3.5.1.2 Launch Procedure. This paragraph describes the sequence of events from receipt of the CFMF hardware at KSC to launch (excluding ground test requirements discussed in Paragraph 3.5.1.1). Figure 3-43 shows the schedule for the integration of CFMF hardware to Spacelab pallet and finally to the Space Shuttle. This schedule shows that approximately 12 working days are required to complete CFMF-to-pallet integration.

The GSE schedule for the loading of the CFMF supply tank is described in Paragraph 3.3.1. Electrical Ground Support Equipment (EGSE) will be required to operate the CFMF up until launch. The supply tank TVS will operate by venting through the T-O umbilical until just prior to launch, then will be closed until orbit is achieved.

3.5.1.3 On-Orbit Operation. The following paragraphs describe the experimental test plan for Phase I, Mission One. Approximately 96 hours would be required to complete all of the first mission objectives. A typical time line for Mission One is given in Figure 3-44. This permits the first 24 hours of on-orbit operation for orbit stabilization and housekeeping.

Table 3-XXIII gives the valve positions, per Figure 3-2, required to accomplish the following mission operations.

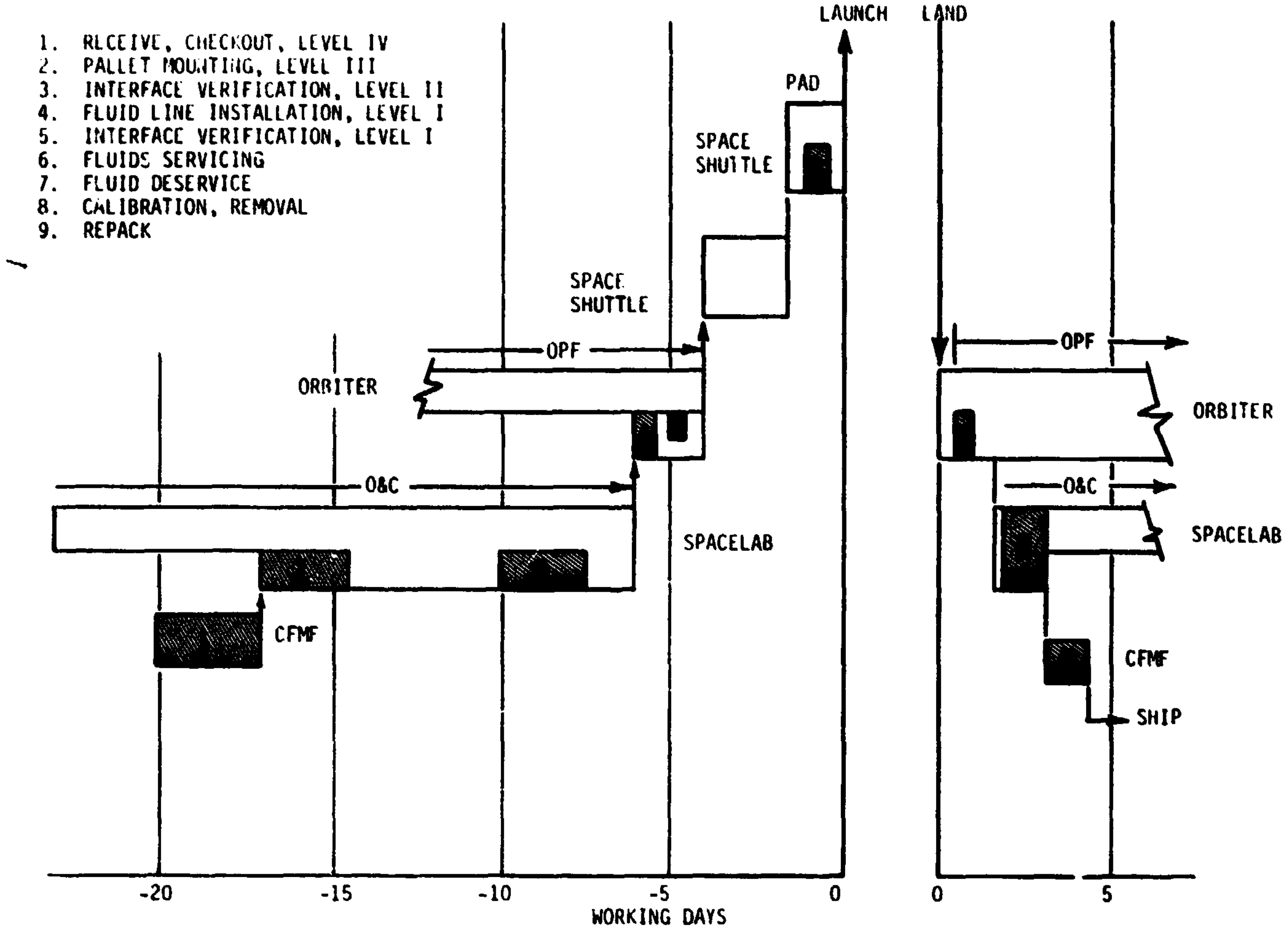


Figure 3-43 CFMF INTEGRATION SCHEDULE

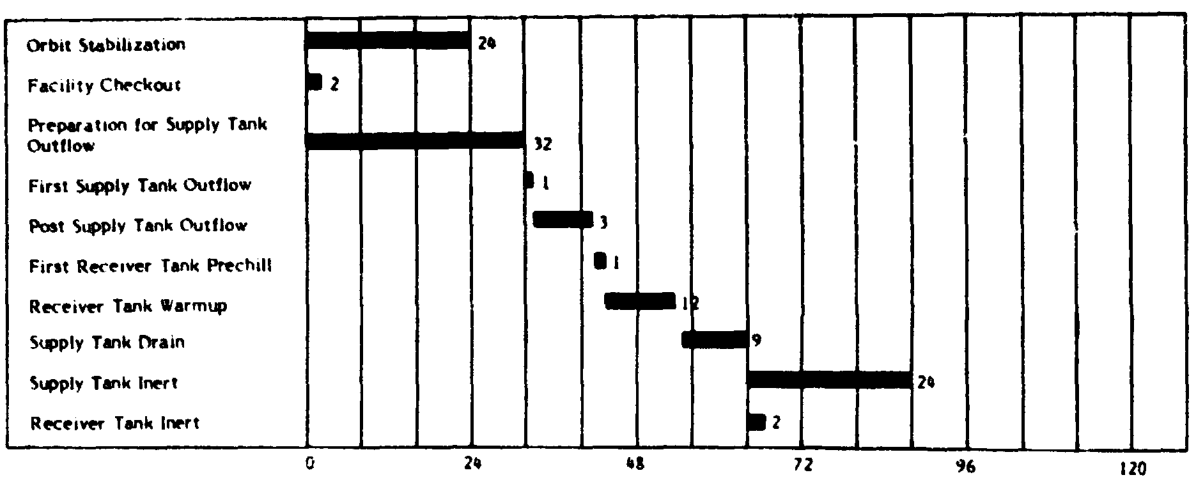


Figure 3-44 PHASE I, MISSION ONE, TIMELINE

TABLE 3-XXIII PHASE I, MISSION ONE, OPERATING PROCEDURE

Operational Mode	SOV† 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	FCV 1
Helium Supply Fill	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	O	C	O	C	C
Supply Tank Fill	C	C	C	C	C	O	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Prelaunch	C	C	M	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Shuttle Launch	O	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Supply Tank TVS	O	C	M	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Supply Tank Pressurization	O	C	M	C	C	C	C	C	M	M	M*	M*	C	C	C	C	C	C	C	C	C
Quality Meter Calibration	O	C	M	C	C	C	C	O	M	M	M*	M*	C	C	C	C	C	C	C	C	M
Supply Tank Outflow	O	C	M	C	C	C	C	O	M	M	M*	M*	C	C	C	C	C	C	C	C	M
Receiver Tank Prechill Charge	O	C	M	C	C	C	O	C	M	M	M*	M*	C	C	C	C	C	C	C	C	M
Receiver Tank Prechill Hold	O	C	M	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Receiver Tank Prechill Vent	O	C	M	O	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Supply Tank Drain	O	C	C	C	C	C	C	O	M	M	M*	M*	C	C	C	C	C	C	C	C	M
Receiver Tank Blowdown	O	C	C	O	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Supply Tank Inerting	O	C	C	C	C	C	C	C	M	M	M*	M*	C	C	C	C	C	C	C	C	C
Receiver Tank Inerting	O	C	C	C	C	C	C	C	C	C	C	C	M	M	M*	M*	C	C	C	C	C
Abort: Prelaunch (T < 4 hrs)	C	C	C	C	O	C	C	C	M	M	M*	M*	C	C	C	C	C	C	C	C	C
Abort: Orbit	O	C	C	C	C	C	C	O	M	M	M*	M*	C	C	C	C	C	C	C	C	O
Abort: Post Landing	C	O	C	C	C	C	C	C	M	M	M*	M*	C	C	C	C	C	C	C	C	C

O - Open

M - Modulate

C - Close

* - Backup

† - Reference Phase I Flow Schematic, Figure 3-2

Facility Checkout. Following orbit insertion, instrument check-out involving the electrical systems and equipment check-out will be initiated. Checkout of the DACS and electrical continuity checks will constitute the electrical system testing.

Preparation for Supply Tank Outflow. The supply tank TVS will be re-activated immediately upon orbit insertion. The microprocessor will monitor supply tank pressures and temperatures to evaluate the effectiveness of the TVS. During this period of no-out flow from the supply line, the retention capability of the capillary device will be determined during the first outflow. During the period of no-outflow, the DACS will monitor vibration levels, temperatures in the supply tank, and the supply tank pressure history. Heat flux into the supply tank will be determined using the TVS mass flow rate and supply tank pressure history.

First Supply Tank Outflow. The first and second primary experimental objectives outlined in Table 2-I will be demonstrated during this period. The outflow sequence will involve pressurization of the supply tank with helium and opening SOV8 and FCV1. The DACS will monitor the capillary device pressure and temperature, supply tank liquid quantity, outflow quality, outflow rate and helium pressurant usage. These measurements will be used to evaluate the response of the supply tank capillary device to transients during start-up and shut-down of the outflow from the supply tank. During this first supply outflow, about 20 percent of the LH_2 will be expelled. The first portion of this outflow will be used to calibrate the quality/density meter. This will be done by flowing liquid hydrogen through QM2 and then through SOV8 and heat exchangers HX1 and HX2.

Post Supply Tank Outflow. Following the outflow operation, a coast period with the TVS active will be initiated to determine the effect of the warm helium pressurant on the supply tank capillary device and the thermodynamic state of the liquid hydrogen. Evaporation inside the channel will be evaluated by measuring the quality of liquid expelled during subsequent outflows.

Receiver Tank Prechill. During the second outflow period, the third and fourth primary experimental objectives, transfer line cooldown and the receiver tank prechill will be accomplished. The CFME tank will be pressurized and outflow will be initiated. Liquid hydrogen will flow through the transfer line into the receiver tank, utilizing the charge, hold and vent sequence as described in Paragraph 2.5.1. Flow into the receiver tank will be terminated when the receiver tank has reached a predetermined pressure. Following charge, the receiver tank will enter a hold period until either the pressure in the receiver tank reaches the maximum tank pressure, or until the average tank wall and fluid temperatures are within approximately 5 percent of each other. The receiver tank will then be vented down to approximately 10.3 kPa (1.5 psi). Charge, hold and vent cycles will be repeated until the average receiver tank wall temperature has reached the prechill target temperature of approximately $110^{o}K$ ($200^{o}R$). Upon completing prechill of the receiver tank, it will be vented down to approximately 10.3 kPa (1.5 psia).

If sufficient LH_2 remains in the supply tank for another receiver tank prechill, it would be necessary to warm the receiver tank to ambient conditions. This could be accomplished with the use of electrical heaters mounted on the tank wall. The second prechill would allow for evaluation of a LH_2 flow rate other than 0.023 Kg/sec (0.05 lb/sec). Following

the last prechill hold, the receiver tank will be vented to approximately 10.3 kPa (1.5 psia) and held 12 hours while the tank warms up. Then the receiver tank will again be vented to 10.3 kPa (1.5 psia) and inerted with helium.

Supply Tank Drain. Following the receiver tank prechill, the volumetric efficiency of the supply tank capillary device will be evaluated. The supply tank will be drained until vapor breaks through the capillary device, at which time the flow rate, supply tank pressure, temperature and the quantity of liquid in the tank will be recorded.

Supply Tank Inerting. With the supply tank drained to approximately three percent residuals, helium inerting will begin. This will be accomplished by venting the supply tank to approximately 10.3 kPa (1.5 psia). Having closed the vent, the tank pressure will be allowed to increase due to heat leak into the tank. At the time the vent is closed, the supply tank temperature will be approximately 14°K (25°R). Based on Reference 3, the heat leak into the tank will be 7.1 w (24.3 Btu/hr); thus, a 24-hour hold would increase the supply tank temperature and pressure to 31°K (56°R) and 303 kPa (44 psia), respectively. The supply tank will again be vented to approximately 10.3 kPa (1.5 psia), then will be pressurized and inerted with helium gas.

Receiver Tank Inerting. The Phase I receiver tank will contain only vapor. Inerting will consist of an initial tank blowdown followed by helium pressurization and a second blowdown and helium repressurization to 124 kPa (18 psia). The last helium pressurization is required to prevent tank collapse upon reentry.

3.5.2 Phase II. The following subparagraphs describe the experimental test plan for both missions of the CFMF Phase II.

3.5.2.1 Ground Test Requirements. The ground test requirements for both missions of Phase II are identical to the requirements for Phase I discussed in Paragraph 3.5.1.1.

3.5.2.2 Launch Procedure. The Phase II launch procedure is identical to the Phase I launch procedure contained in Paragraph 3.5.1.2.

3.5.2.3 On-Orbit Operation, Phase II, Mission Two. Approximately 125 hours will be required to complete all of the second mission objectives; a typical timeline for Mission Two is contained in Figure 3-45. This timeline allows the first 24 hours of on-orbit operation for orbit stabilization and housekeeping. A three-hour time lag is permitted for

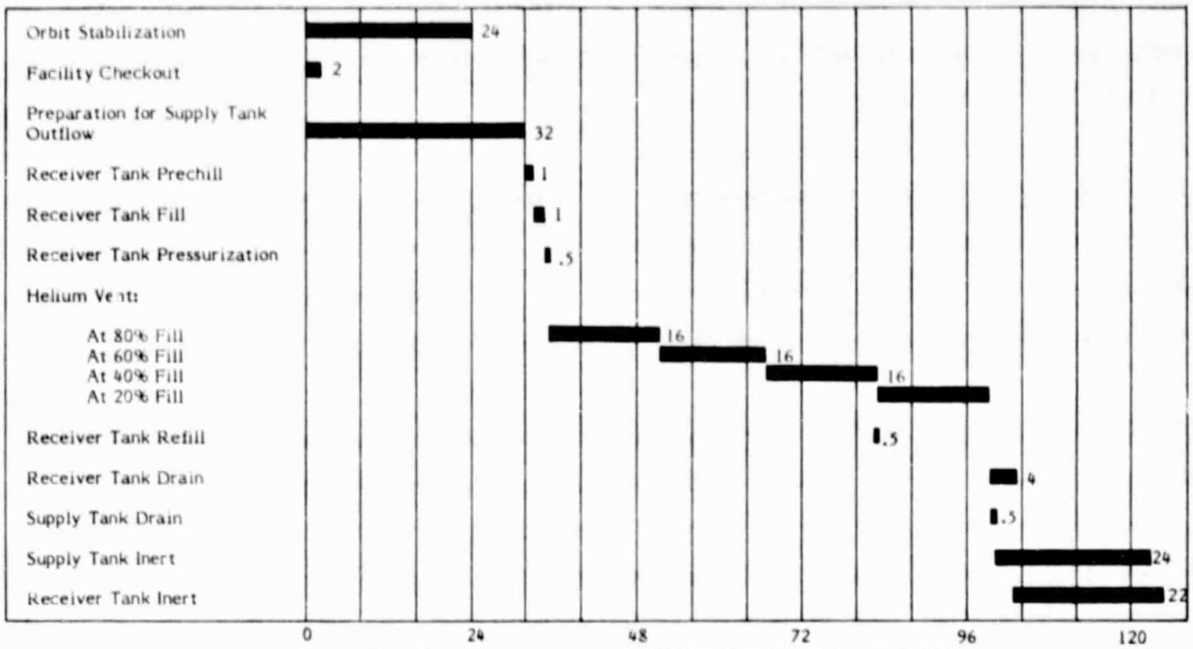


Figure 3-45 PHASE II, MISSION TWO, TIMELINE

RCS engine firing from the time the request is made. Several of the early sequences of operation are similar to that contained in Mission One and are included here for completeness.

Table 3-XXIV gives the valve positions, per Figure 3-14, for the various operations of Mission Two.

Facility Checkout. As in Mission One, instrument and electrical checkouts will be initiated following orbit insertion. Checkout of the DACS and electrical continuity checks constitute the electrical system testing.

Preparation for Supply Tank Outflow. The supply tank TVS will be re-activated immediately upon orbit insertion. During this period, a microprocessor will be monitoring supply tank pressure and temperature to evaluate the effectiveness of the TVS flow/outflow demand. At this point, the DACS will be monitoring vibration levels, temperatures in the transfer line and supply tank, and supply tank pressure. Heat flux to the supply tank will be determined from the TVS mass flow rate and supply tank pressure history. Upon completion of this coast period, steady state supply tank conditions should have been reached and the supply tank will be pressurized to approximately 276 kPa (40 psia) using the ambient helium pressurant. During the pressurization, the supply tank temperature and pressure will be recorded to determine the effect of the ambient helium pressurant on the supply tank LH_2 thermodynamic state.

TABLE 3-XXIV PHASE II, MISSION TWO, OPERATING PROCEDURE

Operational Mode	SOV† 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	FCV 1	2
Helium Supply Fill	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	O	C	O	C	C	C	C	C
Supply Tank Fill	C	C	C	C	C	O	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Prelaunch	C	C	M	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Shuttle Launch	O	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Supply Tank TVS	O	C	M	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Supply Tank Pressurization	O	C	M	C	C	C	C	C	M	M	M*	M*	C	C	C	C	C	C	C	C	C	C	C	C
Receiver Tank Prechill Charge	O	C	M		C	C	O	C	M	M	M*	M*	C	C	C	C	C	C	C	C	C	C	M	C
Receiver Tank Prechill Hold	O	C	M	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Receiver Tank Prechill Vent	O	C	M	O	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Receiver Tank Fill	O	C	M	C	C	C	O	C	M	M	M*	M*	C	C	C	C	C	C	C	C	C	C	M	C
Receiver Tank Pressurization	O	C	M	C	C	C	C	C	C	C	C	C	M	M	M*	M*	C	C	C	C	C	C	C	C
Start Basket Outflow	O	C	M	C	C	C	C	C	C	C	C	C	M	M	M*	M*	C	C	C	C	O	C	C	M
Receiver Tank TVS	O	C	M	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	M	C	C
Receiver Tank Helium Vent	O	C	M	O	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Receiver Tank Drain	O	C	M	C	C	C	C	C	C	C	C	C	M	M	M*	M*	C	C	C	C	C	C	C	M
Supply Tank Drain	O	C	C	C	C	C	C	O	M	M	M*	M*	C	C	C	C	C	C	C	C	C	C	M	C
Receiver Tank Blowdown	O	C	C	O	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	O	C
Supply Tank Blowdown	O	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Receiver Tank Inerting	O	C	C	C	C	C	C	C	C	C	C	C	M	M	M*	M*	C	C	C	C	C	C	C	C
Supply Tank Inerting	O	C	C	C	C	C	C	C	M	M	M*	M*	C	C	C	C	C	C	C	C	C	C	C	C
Abort — Prelaunch (T < 4 hrs)	C	C	C	C	O	C	C	C	M	M	M*	M*	C	C	C	C	C	C	C	C	C	C	C	C
Abort — Orbit	O	C	C	C	C	C	C	O	M	M	M*	M*	M	M	M*	M*	C	C	C	C	O	C	M	M
Abort — Post Landing	C	O	C	C	C	C	C	M	M	M*	M*	C	C	C	C	C	C	C	C	C	C	C	C	C

O - Open

M - Modulate

C - Close

* - Backup

† - Reference Phase II Flow Schematic, Figure 3-14

<u>Receiver Tank Prechill.</u> The receiver tank prechill will be accomplished utilizing the charge, hold and vent technique for Phase I discussed in Paragraph 3.5.1.3. Outflow from the supply tank into the receiver tank will be initiated and continue until the receiver tank pressure reaches approximately 103 kPa (15 psia). Having completed the LH_2 charge, the receiver tank will be locked up until its pressure reaches the maximum working pressure of 276 kPa (40 psia), or until the average receiver tank wall and fluid temperature are within 5 percent of each other. When one of these conditions is met, the receiver tank will be vented to approximately 10.3 kPa (1.5 psia), and the vent then closed. During venting, the vent fluid quality will be monitored to determine if liquid is vented. Having completed the charge, hold and vent cycle, the average tank wall temperature will be determined and compared to the predetermined prechill target temperature of $100^{o}K$ ($180^{o}R$). If the average receiver tank temperature exceeds the target temperature, another charge, hold and vent cycle will be initiated. During the

receiver tank prechill, data will be collected on the supply tank's capability to provide pulsed flow as required by the receiver tank prechill charge period. Receiver tank pressure and temperature histories, transfer line pressures and temperatures, and the gravitational field during transfer will be recorded by the DACS.

Receiver Tank Fill. After prechill, the receiver tank will be filled at a maximum supply tank outflow rate of 22.7 g/sec (0.05 lb/sec). The fill will be completed to the 92.2 percent level, the same fill percentage as the full-scale POTV. During fill, supply tank outflow quality, temperatures and pressures will be recorded, as well as receiver tank pressure, fluid and wall temperatures. This data will be used to determine whether the mixing relations described in Paragraph 2.5 have been met.

Receiver Tank Pressurization. Following fill, the receiver tank will be pressurized with ambient helium to 241 kPa (35 psia). During pressurization, receiver tank temperature and pressure will be monitored to evaluate the impact of ambient pressure on receiver tank LH_2 thermodynamic conditions.

Venting. Liquid outflow from the receiver tank will be initiated using RCS engines for settling. The tank will be drained to the 80 percent fill level. A 12-hour coast period will follow the settling operation during which the liquid hydrogen will assume a low-gravity position within the tank. Venting through the tapered vent tube will be done by opening SOV4. Tank temperature, pressure, vent flow rate and quality will be recorded. If significant quantities of liquid hydrogen are detected escaping through the vent tube, the vent will be closed. The sequence of operations consisting of the settling, coast and venting will be repeated at 60 percent, 40 percent and 20 percent receiver tank fill levels. If venting through the tapered vent tube during coast proves unacceptable due to liquid losses, then helium venting would be accomplished after settling.

Internal Heat Exchanger/Fan TVS. During the coast periods between helium venting, the performance of the TVS and the ability of the internal fan to destratify the tank will be assessed. The thermal performance of the TVS will be determined by measuring the quality, temperature and pressure of the vent flow with QM4, TS7 and PT7. The effect of the fan on stratification and bulk fluid mixing will be evaluated by monitoring temperatures and pressures.

Receiver Tank Drain. Following the helium vent operation at the 20 percent fill level, the receiver tank will be drained until vapor pullthrough occurs. This will be accomplished by settling the LH_2, utilizing the RCS engines. A vapor pullthrough suppression baffle will be used to prevent early vapor ingestion. At pullthrough, the quantity of liquid remaining in the tank, the mass flow rate out of the tank and the tank pressure, will be recorded.

Supply and Receiver Tank Inerting. After draining, the supply and receiver tank residuals will be approximately three percent and helium inerting will begin. Inerting will be accomplished by venting the tanks to approximately 10.3 kPa (1.5 psia), closing the vents and allowing the tank pressures to increase. At the time the vents are closed, the minimum supply and receiver tank temperatures will be approximately $14^{o}K$ ($25^{o}R$). After a 24-hour hold, the supply and receiver tank temperatures and pressures will increase such that only vapor exists in the tanks. This will permit further venting to approximately 10.5 kPa (1.5 psia), after which the supply tank and receiver tanks will be pressurized (and inerted) with ambient helium gas.

3.5.2.4 On-Orbit Operation, Phase II, Mission Three. A typical timeline for this mission is given in Figure 3-46. This figure shows that 112 hours are required to meet mission objectives; the first 24 hours are assumed to be unavailable. Valve positions for mission operations are given in Table 3-XXV.

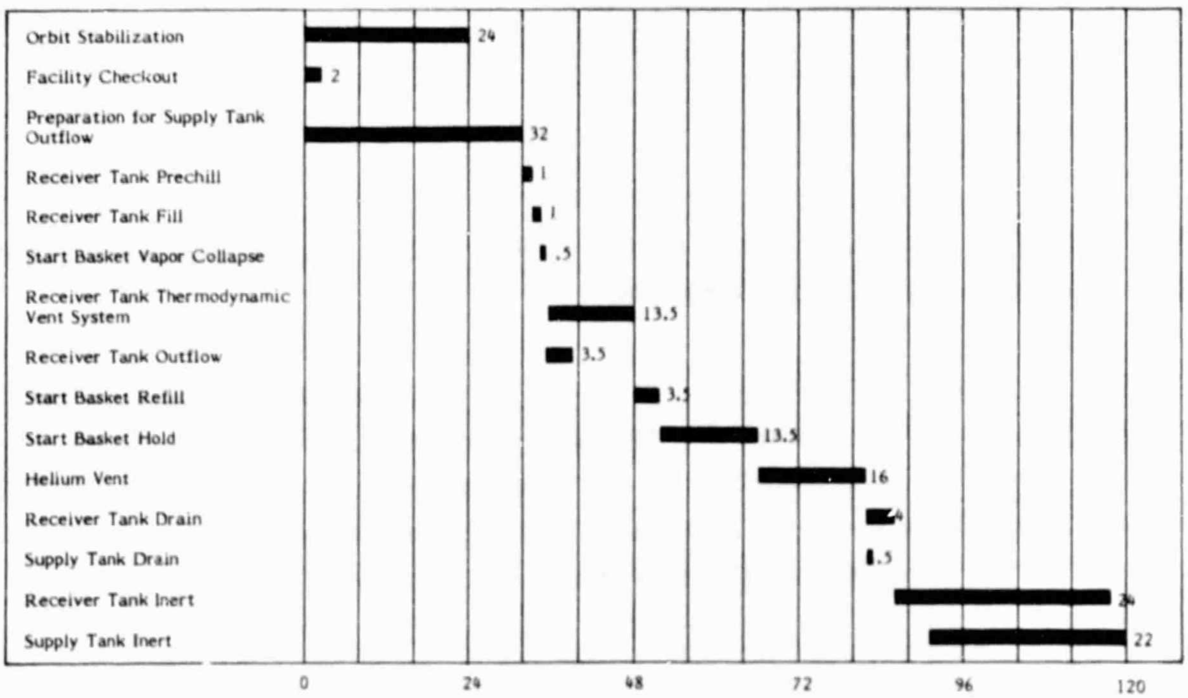


Figure 3-46 PHASE II, MISSION THREE, TIMELINE

TABLE 3-XXV PHASE II, MISSION THREE, OPERATING PROCEDURE

Operational Mode	SOV†																						FCV	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	1	2
Helium Supply Fill	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	O	C	O	C	C	C	C	C
Supply Tank Fill	C	C	C	C	C	O	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Prelaunch	C	C	M	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Shuttle Launch	O	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Supply Tank TVS	O	C	M	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Supply Tank Pressurization	O	C	M	C	C	C	C	C	M	M	M•	M•	C	C	C	C	C	C	C	C	C	C	C	C
Receiver Tank Prechill Charge	O	C	M	C	C	C	O	C	M	M	M•	M•	C	C	C	C	C	C	C	C	C	C	M	C
Receiver Tank Prechill Hold	O	C	M	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Receiver Tank Prechill Vent	O	C	M	O	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Receiver Tank Fill	O	C	M	C	C	C	O	C	M	M	M•	M•	C	C	C	C	C	C	C	C	C	C	M	C
Receiver Tank Pressurization	O	C	M	C	C	C	C	C	C	C	C	C	M	M	M•	M•	C	C	C	C	C	C	C	C
Receiver Tank Helium Vent	O	C	M	O	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Receiver Tank Drain	O	C	M	C	C	C	C	C	C	C	C	C	M	M	M•	M•	C	C	C	C	C	C	C	M
Supply Tank Drain	O	C	C	C	C	C	C	O	M	M	M•	M•	C	C	C	C	C	C	C	C	C	C	M	C
Receiver Tank Blowdown	O	C	C	O	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Supply Tank Blowdown	O	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	O	C
Receiver Tank Inerting	O	C	C	C	C	C	C	C	C	C	C	C	M	M	M•	M•	C	C	C	C	C	C	C	C
Supply Tank Inerting	O	C	C	C	C	C	C	C	M	M	M•	M•	C	C	C	C	C	C	C	C	C	C	C	C
Abort Prelaunch (T < 4 hrs)	C	C	C	C	O	C	C	C	M	M	M•	M•	C	C	C	C	C	C	C	C	C	C	C	C
Abort Orbit	O	C	C	C	C	C	C	O	M	M	M•	M•	M	M	M•	M•	C	C	C	C	O	C	M	M
Abort Post Landing	C	O	C	C	C	C	C	C	M	M	M•	M•	C	C	C	C	C	C	C	C	C	C	C	C

O - Open

M - Modulate

C - Close

• - Backup

† - Reference Phase II Flow Schematic, Figure 3-14

Facility Checkout. The first operation after orbit insertion will be instrument and electrical checkout as in the previous missions.

Preparation for Supply Tank Outflow. Immediately following the facility checkout, the supply tank TVS will be re-activated. During this 32-hour period, steady-state conditions should be reached. Upon completion of this coast period, the supply tank will be pressurized to approximately 276 kPa (40 psia), utilizing the helium pressurant. Supply tank temperatures, pressure and TVS flow rate will be recorded to determine tank performance.

Receiver Tank Prechill. Liquid hydrogen inflow distribution will be split such that 22 percent flows into the start basket and the remainder flows through the inlet jet manifold. This distribution is required for the start basket fill process and it will aid in cooldown of the start basket. Receiver tank prechill will be accomplished utilizing the charge, vent and hold technique, as in Mission Two, until the predetermined prechill target temperature of 100°K (180°R) is reached. During the receiver tank prechill, data similar to that collected in Mission Two will be recorded.

Receiver Tank Fill. Following the receiver tank prechill, the receiver tank will be filled using a maximum supply tank outflow rate of 22.7 g/sec (0.05 lb/sec). The fill will be completed to the 92.2 percent level, the same percent ullage as the full scale POTV. The incoming liquid hydrogen will be distributed in the same manner as described for the receiver tank prechill (22 percent of the flow through the start basket and the remaining through the inlet manifold). The data recorded will be similar to Mission Two with the addition of start basket temperatures.

Start Basket Vapor Collapse. If the use of the subcooled liquid inflow into the start basket fails to eliminate vapor bubbles, bubble collapse will be accomplished by pressurizing the receiver tank with helium. A pressure increase of 34.5 kPa (5 psia) will be used; based on the current start basket design, vapor collapse times of less than 10 minutes should be obtained. If 10 minutes has elapsed since helium injection, and vapor still exists in the start basket, tank pressure will again be increased by 34.5 kPa (5 psia) and the hold process will be repeated. During this operation, the ambient helium pressurization should pose no problems in the operation of the start basket, as the receiver tank is 92 percent full and direct impingement of the pressurant is unlikely. However, injection of ambient temperature helium into a less full tank may present a problem due to the possibility of warm pressurant contact with the start basket. A means of detecting the presence of vapor in zero-g is not presently available. This instrumentation is a development item.

Receiver Tank Thermodynamic Vent Test. Following the vapor collapse, the receiver tank TVS will be activated. Either the internal heat exchanger/fan TVS or the externally wrapped TVS (or both) will be evaluated by measuring the quality, temperature and pressure of the vent outflow. The effect of the internal heat exchanger/fan on the start basket thermal performance will be assessed. Receiver tank temperatures and pressure will be monitored and recorded by the DACS throughout this period.

Receiver Tank Outflow. The RCS primary thrusters will be used to settle the liquid in the receiver tank. Outflow from the receiver tank will be initiated following settling and proceed to the 60 percent fill level. This is the fill level at which the start basket refill testing will be conducted.

Start Basket Refill. Following a 10-hour coast period, the RCS engines will be used to position the liquid away from the start basket prior to refill. With the receiver tank pressurized to 241 kPa (35 psia), outflow from the start basket will be initiated. Shortly after outflow starts, the primary RCS thrusters will settle the liquid in the receiver tank. After the liquid settling, refilling of the start basket will commence and should be complete within one minute. (See Appendix III). During this period, receiver tank temperatures, pressures and start basket temperatures will be recorded. Start basket outflow will continue until the receiver tank reaches the half-full level.

Start Basket Liquid Retention Evaluation. A low-g coast period of 10 hours will commence during which liquid evaporates from the surface of the start basket. The ability of the start basket to retain liquid under these conditions will be evaluated. (This period of time was used in calculating the evaporated liquid volume for the start basket.)

Receiver Tank Drain. Following the helium vent operation, the receiver tank LH_2 will be settled and drained by using the RCS engines. At the time of capillary device breakdown, receiver tank residuals, mass flow rate, tank pressure and temperature will be recorded.

Supply Tank Drain. If the supply tank capillary device did not break down during receiver tank fill, the supply tank will be drained during this operational period until vapor breaks through the capillary device. At this time, the flow rate, pressure and the quantity of liquid in the supply tank will be recorded.

Supply and Receiver Tank Inerting. After draining, the tanks will be vented to approximately 10.3 kPa (1.5 psia). With the vent closed, the tank pressures will be allowed to increase due to the heat leak. Following this, the tanks will be vented once again to 10.3 kPa (1.5 psia) and will be pressurized (and inerted) with ambient helium gas.

4.0 FACILITY DEVELOPMENT PLAN

The facility development plan was generated to provide a guide for the cost effective development of the Cryogenic Fluid Management Facility (CFMF) and to identify long-lead, development or high-cost items. This plan consists of cost and schedule estimates for both phases of the facility and was based on the conceptual design. The approach taken in developing the plan consisted of preparation of a Work Breakdown Structure (WBS), a Master Program Schedule and a major component Bill of Material (BOM) from which facility costs were derived.

4.1 Facility Development Schedule. To prepare a schedule for the cost effective development of the CFMF, it was necessary to generate a WBS identifying the required tasks. From the WBS, a Master Program Schedule was prepared to provide estimates of the time and cost required to design, develop, fabricate, test and provide launch support of the CFMF. In the preparation of the Master Program Schedule, the long lead and development items were identified.

4.1.1 Work Breakdown Structure. The WBS shown in Figure 4-1 provides a graphical definition and display of the work tasks to be accomplished. The upper level represents the 17 major tasks identified for the CFMF Program. These tasks will be controlled at the program management level.

The second level denotes those subtasks which will be controlled at a lower level of management. It is these tasks which will be specifically defined by the CFMF statement of work.

A third level of work breakdown takes the tasks down to the level of the working engineer, technician or mechanic where management control is provided by the Lead Man or Crew Chief. This level of detail was not carried out in this study and is, therefore, not shown on Figure 4-1.

4.1.2 Master Program Schedule. The Master Program Schedule shown in Figure 4-2 was derived from the WBS of Figure 4-1. The key program milestones were identified and the schedule was prepared to meet these milestones. The schedule was then reviewed and modified where necessary to provide a realistic development schedule.

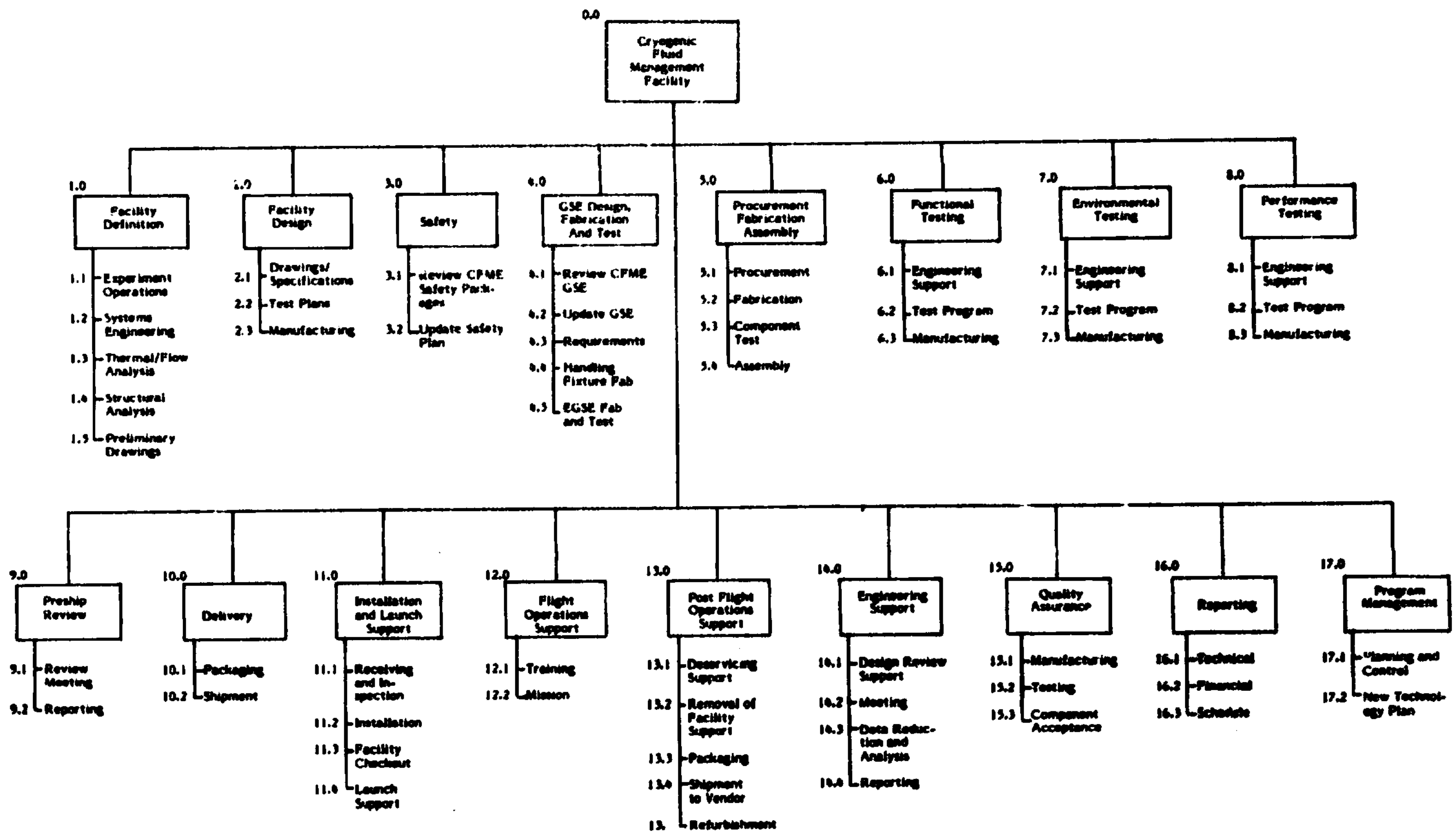


Figure 4-1 WORK BREAKDOWN STRUCTURE

The Master Program Schedule was prepared assuming that the conceptual design work was completed by NASA personnel, eliminating the need for a lengthy design definition phase; however, the detailed analyses of the facility would be necessary. With these assumptions, Figure 4-2 shows a six-month facility definition. Concurrent with the facility definition, review of CFME safety and Ground Support Equipment (GSE) was scheduled to maximize the use of work performed for the CFME design definition study. Procurement and manufacturing tasks were phased to provide a cost effective development. These tasks were influenced by the assumption that, once the facility is launched, a one-year turnaround will exist between subsequent missions.

The Master Program Schedule identifies eight key program milestones:

1. PDR - Preliminary Design Review.
2. FDR - Final Design Review.
3. PSR1 - Phase I Preshipment Review.
4. SSL1 - Space Shuttle Launch, Phase I.
5. PSR2 - Phase II (First Mission) Preshipment Review.
6. SSL2 - Space Shuttle Launch, Phase II (First Mission).
7. PSR3 - Phase II (Second Mission) Preshipment Review.
8. SSL3 - Space Shuttle Launch, Phase II (Second Mission).

The PDR will be held at completion of the facility definition; the FDR, concluding the facility design task for both phases of the facility, is scheduled for 14 months after contract go-ahead. These design reviews will also be required for approval of long-lead procurement items with procurement of the CFME supply tank hardware to begin after PDR. PSR-1 is scheduled for 44 months after contract go-ahead with the first launch 3 months later. PRS-2, PRS-3 and their associated lauches follow at yearly intervals. A total span time of 76 months will be required for the CFMF contract.

4.1 Long-Lead Procurement Items. Long-lead items were identified as those items requiring more than 26 weeks from the time of purchase to delivery. The long-lead items, excluding development items, are:

1.	Temperature sensors	26 weeks
2.	Quality meter	52 weeks
3.	Volumetric flow meter	52 weeks

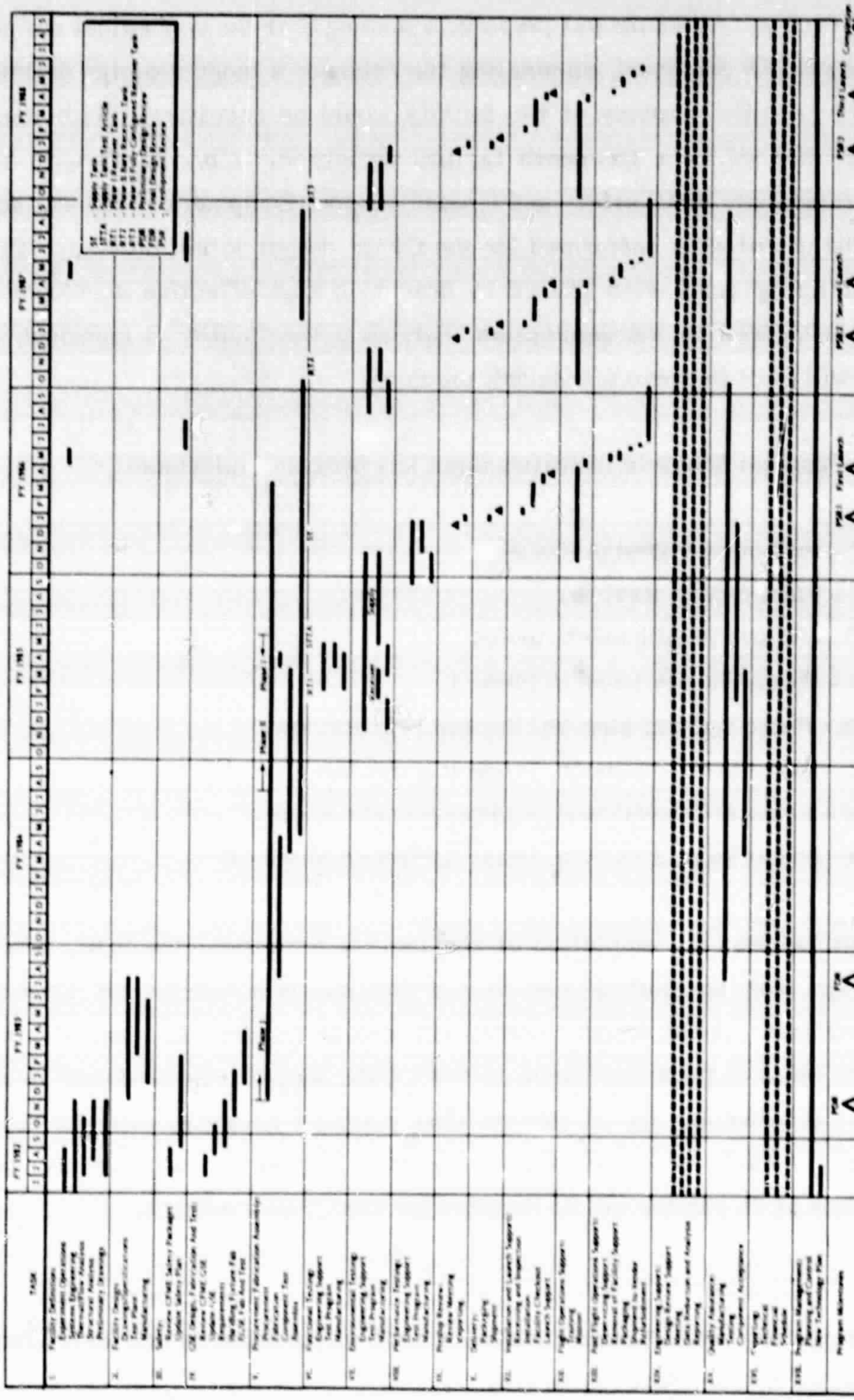


Figure 4-2 MASTER PROGRAM SCHEDULE

4.	Superfloc insulation	32 weeks
5.	Receiver tank girth rings	26 weeks

4.1.4 Development Items. To meet the schedule shown in Figure 4-2, it was assumed that certain critical items were developed prior to their need for CFMF. This may require that development and testing begin prior to contract go-ahead. The major development items for the CFMF are:

1. Quantity gauging systems
2. Quality/density flow measurement
3. Receiver tank start basket
4. Zero-g vapor/liquid detectors

4.2 Facility Costs. Rough Order of Magnitude (ROM) cost estimates were prepared for each phase of the facility. The WBS, Master Program Schedule and a component Bill of Materials (BOM), defining the procurement items, provided the basis for this cost estimate.

The ROM estimates were developed by each contributing department estimating their manpower requirements and costs for the various phases of the facility. After each departmental estimate was made, they were forwarded to the Contracts Department and combined to form overall total costs. If a departmental estimate was out of line with the scope of the defined task, clarification of the task and a resulting adjustment of the departmental estimate was made. In a meeting of the involved department managers, the overall costs were further clarified and refined to realistically reflect the conceptual design of the facility. The overall cost estimates were then submitted to the Division Manager for approval and release. This estimating procedure was used to provide a realistic and comprehensive cost estimate for the Cryogenic Fluid Management Facility.

4.2.1 Bill of Materials (BOM). Facility hardware costs were estimated by generating a BOM comprised of all components required for each phase of the facility. These components were taken directly from the facility conceptual design drawings; their costs were then determined from vendor information. The BOM is given in Appendix II and is broken down into: (1) hardware common to both Phases I and II, (2) Phase I hardware and (3) Phase II hardware. Items shown under Phase I and Phase II hardware are those items required for only those phases.

4.2.2 Cost Estimate. The ROM cost is divided into six program elements which, when totaled, form the cost required to develop, fabricate and provide support for the CFMF. The six elements and their cost estimates are:

Program Element	ROM Cost
Analysis and Design	$ 800,000
Qualification	$ 700,000
Phase I, Mission One	$1,300,000
Phase II, Mission Two	$1,100,000
Phase II, Mission Three	$ 600,000
CFME Tank	$3,000,000
TOTAL Program Cost	$7,500,000

These cost estimates are expressed in December 1980 dollars. A description of each element is given in the following paragraphs.

Analysis and Design. The analysis and design effort is primarily an engineering task. It involves producing the drawings and specifications required to fabricate the Phase I CFMF hardware (exclusive of the CFME supply tank and its associated hardware).

Qualification. This element consists of the testing required to flight qualify all phases of the CFMF hardware (exclusive of CFME hardware). These tests will include environmental and mission simulation testing.

Phase I, Mission One. The Phase I element is fabrication, assembly and performance testing of the Phase I flight hardware. These costs also include preflight, flight and postflight engineering support.

Phase II, Mission Two. This element consists of converting the facility from the large Phase I receiver tank to the smaller Phase II receiver tank. Hardware changes associated with Phase II are included in this element. Phase II also contains preflight, flight and postflight engineering support.

Phase II, Mission Three. This element consists of modifying the Phase II, Mission Two, receiver tank to incorporate a fluid acquisition device and its associated hardware. Preflight, flight and postflight engineering support is included.

CFME Tank. The fabrication, assembly, qualification test, and system integration of the CFME tank is included in this program element. It was assumed that a set of drawings and specifications for this tank will be furnished by the Government.

4.2.3 Cost Estimates Allocated by Fiscal Year. The cost estimates given in Paragraph 4.2.2 are expected to be expended per fiscal year in the amounts shown below. It should be noted that these amounts are expressed in December 1980 dollars.

Fisal Year	CFME Tank	Balance of System	Annual Total
1982	$ 80,000	$ 200,000	$ 280,000
1983	1,525,000	950,000	2,475,000
1984	1,395,000	875,000	2,270,000
1985	-0-	975,000	975,000
1986	-0-	800,000	800,000
1987	-0-	500,000	500,000
1988	-0-	200,000	200,000
TOTALS	$3,000,000	$4,500,000	$7,500,000

5.0 CONCLUSIONS AND RECOMMENDATIONS

Conclusions. The Cryogenic Fluid Management Facility (CFMF) defined by this study will be capable of demonstrating on-orbit cryogenic liquid transfer. The specific technologies necessary to accomplish this are:

- Liquid acquisition and expulsion
- Transfer line cooldown
- Tank cooldown
- Tank fill (nonvented liquid transfer)
- Nonvented tank refill capability
- Start basket performance
- Mass gauging
- Quality and mass flow measurements

The design of the facility was tailored to provide the capability for proving these technologies.

Existing ground support equipment (GSE) for the liquid hydrogen filling of the supply tank may be used without extensive modifications. The additional GSE required to support the facility currently exists at Kennedy Space Center (KSC).

The Safety and Hazard Analysis showed that no single point failure of the CFMF will cause an unsafe condition on the launch pad or in orbit. Use of the Fuel Cell Servicing System for loading the CFMF supply tank will not result in hazards greater than similar cryogenic loading operations at KSC.

The design, development, testing, fabrication and operation of the CFMF will require a span time of approximately seven years. The overall program cost will be $7.5M (in December 1980 dollars).

Recommendations. A number of hardware development items and Shuttle operational unknowns were identified in this study. Instrumentation and hardware development required for the CFMF are:

- Mass gauging
- Quality measurement

- Volumetric flow measurement
- Start basket
- Screen channel device
- Thermodynamic vent system
- Zero-g liquid/vapor detectors

The Shuttle operational unknowns that need to be determined are:

- Payload flight qualification requirements
- Payload safety requirements
- Prelaunch facility servicing constraints

These items can be found in the Payload Accommodations Handbook; however, there is a high degree of uncertainty and conflicting information. In addition to the operational unknowns, an assessment of the potential and cost for GSE modifications to meet the CFMF launch requirements should be conducted.

To ensure the efficient and timely development of the CFMF, it is recommended that research and development of the hardware development items and resolution of the Shuttle operational unknowns begin as soon as possible.

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APPENDIX I

CFMF-FAULT HAZARD ANALYSIS

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE I

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Solenoid Operated Valve SOV17	Fails to open.	0.00081	Normally closed. Opens to fill PV1-4 with gaseous He at 28.9 MPa (4200 psia).	Unable to fill PV1-4.	Electrical failure.			Filled prior to pallet insertion in Shuttle. Replace valve.
	Fails to close after opened (includes leaks).		Closes to lock off PV1-4 when filled and pressurized.	Loss of pressurization.				Filled prior to pallet insertion in Shuttle. Replace valve.
Solenoid Operated Valve SOV19	Fails to open.	0.00081	Normally closed. Opens to fill PV5-9 with gaseous He at 20.7 MPa (3000 psia).	Unable to fill.	Electrical failure.			Filled prior to pallet insertion in Shuttle. Replace valve.
	Fails to close after opened (includes leaks).		Closes to lock off PV5-9 when filled and pressurized.	Loss of pressurization.				Filled prior to pallet insertion in Shuttle. Replace valve.
Solenoid Operated Valve SOV20	Fails to open.	0.00081	Normally closed. Opens to allow PV1-4 to vent. Closes to prevent H_2 contamination after PV1-4 has been vented.	Unable to vent. If PV1-4 not depleted through normal use, Shuttle will land with PVs partially pressurized.	Electrical failure.	PT8		
	Fails to close after opened (includes leaks).			Possible H_2 contamination of He PVs.				
Solenoid Operated Valve SOV18	Fails to open.	0.00081	Normally closed. Opens to allow PV 5-9 to vent. Closes to prevent H_2 contamination after PV5-9 has been vented.	Unable to vent PVs 5-9. If PV5-9 not depleted through normal use, Shuttle will land with PVs partially pressurized.	Electrical failure.	PT9		

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE I (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Solenoid Operated Valve SOV18	Fails to close after opened (includes leaks).			Possible H_2 contamination of He PVs.				
Temperature Sensors TS8 and TS9	Fails to send signal to DACS. Sends false signal to DACS.	0.00005	Senses temperature of pressurized He gas and sends signal to DACS.	DACS will utilize signal from temperature sensors and pressure transducer to determine He quantity remaining. If DACS senses quantity of remaining He is just sufficient to dump remaining LH_2 and inert supply tank, the experiment will be aborted and the tank dumped and inerted.	Electrical failure.	PT8/PT9.		Experiment terminated.
Pressure Transducers PT8 and PT9	Fails to send signal to DACS. Sends false low signal.	0.00045	Senses pressure of PVs 1-4/PVs 5-9 as applicable and sends signal to DACS. DACS will open SOV19/20 if pressure in He line is over pressure.	DACS will utilize signal from temperature sensors and pressure transducer to determine He quantity remaining. If DACS senses quantity of remaining He is just sufficient to dump remaining LH_2 and inert supply tank, the experiment will be aborted and the tank dumped and inerted.	Electrical failure.	SOV19/SOV20 as applicable. TS8/TS9.		Experiment terminated.

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE I (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Solenoid Operated Valves SOV12/SOV11	Fails to close after open (including leaks).			See Remarks.		False low signal from PT10.		This failure is beyond the Single Point Failure Concept. For SOV12 or SOV11 to fail, SOV10 or SOV9 would have failed first.
Filter F1	Filter clogs.	0.00001	Filters high pressure GHe flow to orifice (FO2).	Reduced/shutoff of flow through filter and orifice and reduced pressurant to supply tank.	Contaminated filter at GHe interface.			He should be filtered prior to ground fill interface.
Flow Orifice FO2	Clogged orifice.	0.00001	Reduces high pressure GHe to pressure of 276 KPa (40 psi) by choking flow.	Shutoff of He pressurant to supply tank.	Filter clogging or disintegration. See Remarks.	Filter F1.		This is beyond Single Point Failure Concept.
Temperature Sensor TS3	Sends false signal (high or low). Fails to send signal.	0.00005	Senses temperature of GHe after passing through FO2. Signal received by DACS.	None. DACS uses signal for expulsion pressurant information only.	Flow reduction from clogged filter or orifice. Electrical failure.	F1/FO2.		
Pressure Transducer PT3	Sends false signal (high or low). Fails to send signal.	0.00045	Senses pressure of GHe after passing through FO2. Signal received by DACS.	None. DACS uses signal for expulsion pressurant information only.	Flow reduction from clogged filter or orifice. Electrical failure.	F1/FO2.		
Flow Orifice FO1	Orifice clogs.	0.00001	Reduces pressure and controls flow of LH_2 from supply tank to VCS.	Loss of thermal control of supply tank. Could overpressure supply tank.	Contaminants in LH_2 or supply tank.			Can vent VCS through SOV3 if identifiable from TS within supply tank and/or TS1 and PT1. RV1 will relieve overpressurization of supply tank.

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE I (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That Cause Potential Failures	Further Analysis Required	Remarks
Pressure Transducers PT8 and PT9	Sends false high signal.			DACS will send signal to sequentially open SOV1 and then SOV19/SOV20 (as applicable). Could deplete entire contents of applicable high pressure He system.				Could terminate experiment. Unable to clump or inert supply tank.
Solenoid Operated Valves SOV10/SOV9	Fails to open (SOV10 or SOV9).	0.00081	Receives signal from PT1 (supply tank pressure) through DACS. If PT10 senses low pressure, SOV10 will open and then close. SOV9 will then open and close to allow He pressurant in the supply tank.	None. DACS will sense sequence failure and shift operation to SOV 12 and 13.	Electrical failure.	False high signal from PT10.		
	Fails to close after open (including leaks).			None. DACS will sense sequence failure and shift operation to SOV 12 and 13.		False low signal from PT10.		
Solenoid Operated Valves SOV12/SOV11	Fails to open (SOV12 or SOV11).	0.00081	Normally closed. Redundant system for SOV10/SOV9. If SOV10/SOV9 fails to operate in proper sequence, DACS will automatically shift operation to SOV 12/SOV11.	See Remarks.	Electrical failure. See Remarks.	False high signal from PT10.		This failure is beyond the Single Point Failure Concept. For SOV 12 or SOV11 to fail, SOV10 or SOV9 would have failed first.

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE I (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Flow Control Valve FCV1	Fails to open.	0.00036	Receives signal from DACS using supply tank pressure and flow rate to maintain scheduled flow.	Flow to receiver tank reduced.	Electrical failure.	PT10, QM2.		May be sufficient to terminate experiment.
				Flow stopped to receiver tank.	Electrical failure.			Experiment terminated. Must land with remaining fluid in supply tank.
	Fails to close (including leaks).			Unable to maintain scheduled flow.	Electrical failure.			Flow terminated by SOV7 and SOV8.
Check Valve CV1	Fails open.	0.00005	Prevents pressure surges upstream of CV1 from returning to supply tank.	Reversed flow could force liquid in supply tank away from screen device and allow gaseous pressurant to penetrate screen.				When pressure surges in CV1 line terminated, cycle could continue and fluid in receiver tank would be degraded.
	Fails closed.			Flow stopped to receiver tank.	Contaminants in LH_2 or supply tank.			Experiment terminated.
Quality Meter QM2	Sends false high signal to DACS.	0.0015	Measures volumetric flow rate (q) and density (ρ) of supply tank fluid. Sends signal to DACS to determine mass flow rate of liquid from supply tank. In conjunction with QM1, QM3, QM4 and QM5 will determine accuracy of mass gauging system.	Reduced flow from supply tank to receiver tank. Unable to calibrate mass gauging system.				Primarily used in conjunction with QM1, QM 3, QM4 and QM5 to determine accuracy of mass gauging system.
	Sends false low signal to DACS.			Increased flow from supply tank to receiver tank. Unable to calibrate mass gauging system.				
	Fails to send signal.			Could shut down FCV1.	Electrical failure.			Experiment terminated.

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE I (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Temperature Sensor TS4	Sends false low/high signal to DACS.	0.00005	Senses temperature of liquid downstream of QM2. Sends signal to DACS for information only.	None. Temperature is for information only.				None.
	Fails to send signal.			Same as above.	Electrical failure.			
Pressure Transducer PT4	Sends false low/high signal to DACS.	0.00045	Senses pressure of liquid downstream of QM2. Sends signal to DACS for information only.	None. Signal is for information only.				None.
	Fails to send signal.			Same as above.	Electrical failure.			
Solenoid Operated Valve SOV7	Fails to open.	0.00081	Normally closed. Opens to allow liquid from supply tank to receiver tank.	No flow from supply tank to receiver tank.	Electrical failure.			Supply tank liquid could be vented through SOV8 and SOV1.
	Fails to close (including leaks).			Could overpressure receiver tank.				RV2 will relieve pressure over 276 KPa (40 psia).
Relief Valve RV4	Fails to relieve.	0.00005	Relieves trapped pressure in line between FCV1 and SOV7.	Overpressure of line between FCV1 and SOV7.		Electrical failure. FCV1 and SOV7.		PT4 can sense overpressure in line. SOV8 could be opened to relieve overpressure. Line can withstand 6.895 MPa (1000 psi).
	Fails open.			The line between RV4 and SOV1/BD1 would be pressurized from 276 to 414 KPa (40 to 60 psia). When on orbit and SOV1 is opened, supply tank pressure will be vented.				Experiment terminated.

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE I (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Temperature Sensor TS7	Sends false low/high signal to DACS.	0.00005	Senses temperature of liquid entering receiver tank. Sends signal to DACS for information only.	None. Temperature is for information only.				
	Fails to send signal.			Same as above.	Electrical failure.			
Pressure Transducer PT7	Sends false low/high signal to DACS.	0.00045	Senses pressure of liquid entering receiver tank. Sends signal to DACS for information only.	None. Signal is for information only.				
	Fails to send signal.			Same as above.	Electrical failure.			
Temperature Sensors TS13-62	Sends false low/high signal to DACS.	0.00005	Senses temperature of liquid within receiver tank. Used to determine average tank temperature during prechill. Sends signal to DACS for information during transfer of fluid in and out of receiver tank.	None. Temperature is for information only.				
	Fails to send signal.			Same as above.	Electrical failure.			
Temperature Sensor TS2	Sends false low/high signal to DACS.	0.00005	Senses temperature of liquid exiting receiver tank. Sends signal to DACS for comparison.	None. Temperature is for information only.				
	Fails to send signal.			Same as above.	Electrical failure.			

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE I (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Pressure Transducer PT2	Sends false low signal to DACS.	0.00045	Senses receiver tank pressure and sends signal to DACS. If pressure is excessive, DACS will open SOV4 to relieve pressure.	Could overpressure receiver tank.				RV2 will relieve overpressure if SOV4 fails to open.
Quality Meter QM3	Sends false high/low signal to DACS.	0.0015	Measures volumetric flow rate (q) and density (ρ) of fluid. Sends signal to DACS to determine mass flow rate of liquid leaving receiver tank. In conjunction with QM1 and QM2, will determine accuracy of mass gauging system.	Unable to calibrate mass gauging system.				
	Fails to send signal.			Same as above.	Electrical failure.			
Solenoid Operated Valve SOV4	Fails to open.	0.00081	Normally closed. Opens when PT4 senses high pressure in receiver tank and when fluid leaves the receiver tank.	a. If opening was for high receiver tank pressure, no effect. RV2 will relieve excess pressure.	Electrical failure.	False low pressure. Signal from PT2.		a. RV2 will relieve excess pressure.
				b. If opening was to vent receiver tank fluid, no flow will leave tank through SOV4. Experiment terminated.				b. Could blow down receiver tank through SOV7 and SOV8. Close SOV7 and blow down supply tank through FCV1 and SOV8.

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE I (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Solenoid Operated Valve SOV4	Fails to close after opened (including leaks).			a. If fails to close, receiver tank will be blown down down through SOV1. b. If leak is very small, no effect.		False high pressure signal from PT2.		a. Experiment terminated. Could inert receiver by first venting supply tank and closing SOV3. Close SOV1 and inert receiver tank.
Relief Valve RV2	Fails to relieve. See Remarks.	0.00005	Redundant protection from overpressure of receiver tank.	Overpressure of receiver tank. See Remarks.				This failure is beyond the Single Point Failure Concept. Before RV2 could fail to relieve, the tank would have to have excess pressure and SOV4 would have to fail to open.
	Fails open.			Receiver tank will be blown down through SOV1.				Experiment terminated. Could inert receiver by first venting supply tank and closing SOV3. Close SOV1 and inert receiver tank.
Solenoid Operated Valves SOV14/SOV13	Fails to open (SOV14 or SOV 13).	0.00081	Normally closed. Receives signal from PT2 (receiver tank pressure) through DACS. If PT2 senses low pressure, SOV14 will open and then close. SOV13 will then open and close to allow He pressurant from PV5-9 to enter the receiver tank.	None. DACS will sense sequence failure and shift operation to SOV 16 and 15.	Electrical failure.	False high signal from PT2.		

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE I (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Solenoid Operated Valves SOV14/SOV 13	Fails to close after open (including leaks).			Same as above.		False low signal from PT10.		
Solenoid Operated Valves SOV16/SOV 15	Fails to open (SOV16 or SOV 15).	0.00081	Normally closed. Redundant system for SOV14/SOV13. If SOV14/SOV13 fail to operate in proper sequence.	See Remarks.	Electrical failure. See Remarks.			This failure is beyond the Single Point Failure Concept. For SOV 16 or SOV15 to fail, SOV14 or SOV13 would have failed first.
	Fails to close after open (including leaks).			See Remarks.				
Filter F2	Filter clogs.	0.00001	Filters high pressure GHe flow to FO3.	Reduced/shutoff of flow through filter and orifice, and reduced pressurant to receiver tank.	Contaminated filter at GHe interface.			He should be filtered prior to ground fill interface.
Flow Orifice FO3	Clogged orifice.	0.00001	Reduces high pressure GHe to pressure of 276 KPa (40 psi) by choking flow.	Shutoff of He pressurant to receiver tank.	Filter clogging or disintegration. See Remarks.	Filter F2.		This is beyond Single Point Failure Concept.
Temperature Sensor TS6	Sends false signal (high or low). Fails to send signal.	0.00005	Senses temperature of GHe after passing through FO3. Signal received by DACS.	None. DACS uses signal for expulsion pressurant information only.	Flow reduction from clogged filter or orifice. Electrical failure.	F2/FO3.		
Pressure Transducer PT6	Sends false signal (high or low). Fails to send signal.	0.00045	Senses pressure of GHe after passing through FO3. Signal received by DACS.	None. DACS uses signal for expulsion pressurant information only.	Flow reduction from clogged filter or orifice. Electrical failure.	F2/FO3.		

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE I (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Solenoid Operated Valve SOV8	Fails to open.	0.00081	Normally closed. Vent valve for supply tank (blowdown). When open, allows fluid from supply tank to be vented. Also used as vent for He purge and mass gauging system calibration.	a. During blowdown: Unable to blow down tank and purge in normal manner. See Remarks. b. During He purge: Unable to purge in normal manner. Unable to calibrate QM2.	Electrical failure.			a. Could blow down through receiver tank if sufficient He pressurant is available. b. Purge could be vented through receiver tank after fluid in receiver tank vented.
	Fails to close (including leaks).			a. Unable to transfer liquid to receiver tank. b. If leak is small, no effect.				a. Experiment terminated. b. If leak is large, see a.
Heat Exchanger HX1	Fails to operate.	0.00081	Electrical heat exchange. Will heat liquid to vapor stage. Receives signal from TS5/PT5 through DACS.	Inaccurate measurement from VM1. Will be unable to calibrate mass gauging system.	Electrical failure	Inaccurate signal from TS5/PT5.		
	Fails to turn off.			Possibility of overheating line.				Thermostatically protected.
Pressure Transducer PT5	Sends false high signal.	0.00045	Senses pressure of vapor upstream of HX1. Sends signal to DACS. If pressure is below saturation pressure, DACS will turn on HX1.	HX1 would operate longer than required resulting in warming fluid above saturation pressure. Would tend to invalidate quality meter calibration.				If PT5 malfunctions, only the mass gauging system calibration would be jeopardized.

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE I (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Pressure Transducer PT5	Sends false low signal.			HX1 would turn off prior to fluid reaching saturation pressure resulting in invalid mass gauging system calibration.				
	Fails to send signal.			HX1 may not operate resulting in cold fluid reaching VM1. Invalid mass gauging system calibration.	Electrical failure.			
Temperature Sensor TS5	Sends false high signal.	0.00005	Senses temperature of vapor upstream of HX1. Sends signal to DACS. If temperature below saturation temperature, DACS will turn on HX1.	HX1 would turn off prior to reaching saturation temperature resulting in invalid quality meter calibration.				If TS5 malfunctions, only the mass gauging system calibration would be jeopardized.
	Sends false low signal.			HX1 would operate longer than required resulting in warmer fluid above saturation temperature. Would tend to invalidate quality meter calibration.				
	Fails to send signal.			HX1 may not operate resulting in cold fluid reaching VM1. Invalid quality meter calibration.	Electrical failure.			

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE I (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Heat Exchanger HX2	Fails to operate (if electrical).	0.00081	Warms fluid from HX1 prior to VM1 to insure an accurate reading from VM1.	Inaccurate measurement from VM1. Will be unable to calibrate mass gauging system.	Electrical failure.			
	Fails to turn off (if electrical).			None. Unit will be on during flow through SOV8.				Thermostatically protected (if electrical).
Volumetric Meter VM1	Sends false low/high signal to DACS.	0.00015	Measures volumetric flow rate (q) of flow through vent line. Signal sent to DACS and used for calibration of QM2 and quality meter.	Inaccurate calibration of QM2.				
	Fails to send signal.			Same as above.	Electrical failure.			
Temperature Sensor TS10	Sends false low/high signal to DACS.	0.00005	Senses temperature of vapor from VM1. Sends signal to DACS for information only.	None. Used for information only.				May be used to control HX2 if HX2 is electrical.
	Fails to send signal.			Same as above.	Electrical failure.			
Quality Meter QM1	Sends false signal to DACS (high/low).	0.0015	Measure volumetric flow rate (q) and density (ρ) of VCS coolant fluid. Sends signal to DACS to determine flow rate of fluid through VCS. In conjunction with QM2, QM3, QM4 and QM5, will determine accuracy of quality meter. Determines effectiveness of VCS.	Inaccurate mass gauging system calibration.				
	Fails to send signal.			Same as above.	Electrical failure.			

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE I (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Temperature Sensor TS1	Sends false signal to DACS (high/low).	0.00005	Senses temperature of VCS coolant exiting QM1. Sends signal to DACS.	None. Signal is for information only.				
	Fails to send signal.			Same as above.	Electrical failure.			
Pressure Transducer PT1	Sends false signal to DACS (high/low).	0.00045	Senses pressure of VCS coolant exiting QM1. Sends signal to DACS.	None. Signal is for information only.				
	Fails to send signal.			Same as above.	Electrical failure.			
Solenoid Operated Valve SOV3	Fails to open.	0.00081	Normally closed. Opens to allow flow of VCS fluid to vent. Receives signal from DACS to open when PT 10 senses high pressure in supply tank.	No flow through VCS. Increased heat leak due to less cooling through VCS causing increased pressure in supply tank.	Electrical failure.	False low signal from PT10.		If overpressure of supply tank is imminent, RV1 will relieve pressure.
	Fails to close (includes leaks).			a. Depletion of supply tank fluid. b. Leaks: If minor leak, no effect.		False high signal from PT10.		a. Experiment terminated. b. If leak is large, see a.
Pressure Transducer PT10	Sends false low signal to DACS.	0.00045	Senses supply tank pressure. If pressure is high, will send signal through DACS to open SOV 3 to increase VCS coolant fluid to decrease heat leak.	Will close SOV3 to reduce VCS coolant and increase heat leak to supply tank. Increase of supply tank pressure. See Remarks.				If pressure is excessive, RV1 will relieve pressure.

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE I (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Pressure Transducer PT10	Sends false high signal to DACS.			Will open SOV3 to increase VCS coolant. Partial depletion of supply tank fluid. Decrease of pressure in supply tank.				
	Fails to send signal to DACS.			DACS could interpret signal as low pressure signal and close SOV3. Pressure in tank will increase due to increased heat leak. See Remarks.	Electrical failure.			If pressure is excessive, RV1 will relieve pressure.
Relief Valve RV1	Fails to relieve. See Remarks.	0.00005	Protective valve to prevent overpressure of supply tank in case of FCV1 and SOV3 failure to open or electrical failure.	Overpressure of supply line. See Remarks.	Electrical failure.			This failure is beyond the Single Point Failure Concept. Before RV1 could fail to relieve, FCV1 and SOV 3 would first have to fail closed (for instance, electrical failure).
	Fails open.			Loss of pressure of of supply tank.				Experiment terminated.

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE I (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Solenoid Operated Valve SOV1	Fails to open.	0.00081	Normally closed until "on orbit," then normally open. Vent valve to orbiter interface vent. Opens at other times as follows:	Experiment terminated. See Remarks.	Electrical failure.	PT8/SOV20, PT9/SOV18.		System protected against overpressure by BD1.
	Fails to close (including leaks).		a. PT8 senses overpressure of PV1-4 and SOV20 opens. b. PT9 senses overpressure of PV5-9 and SOV18 opens. Closed after experiment completed for He purge and pad.	Unable to have He pad after purge.				
Burst Disc BD1	Fails to burst. See Remarks.		Protective system to prevent overpressure of entire system.	Overpressure of system. See Remarks.				This failure is beyond the Single Point Failure Concept.
Solenoid Operated Valve SOV2	Fails to open.	0.00081	Normally closed. Horizontal drain valve. Open only for ground LH_2 drain to C3 (T-0 umbilical). (Used only if system failure results in LH_2 in supply tank upon landing.)	Unable to drain LH_2 through SOV 2. See Remarks.	Electrical failure.			Ground use only. Could partially empty supply tank through SOV5 and then hook up GHe supply to C6 to vaporize remaining LH_2. Change valve after inert.
	Fails to close (includes leaks).			None. At T-0 C3 umbilical disconnected and sealed. See Remarks.				When C3 umbilical disconnected, provides seal against leakage.

C-3

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE I (Concluded)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Solenoid Operated Valve SOV5	Fails to open.	0.00081	Normally closed. Vertical drain valve. Open only for ground LH_2 drain on launch pad to C3 (T-O umbilical).	Unable to drain LH_2 through SOV 5. See Remarks.	Electrical failure.			Ground use only. Could partially empty supply tank through SOV2 and then hook up GHe supply to C6 to vaporize remaining LH_2. Change valve after inert.
	Fails to close (includes leaks).			None. At T-O C3 umbilical disconnected and sealed. See Remarks.				When C3 umbilical disconnected, provides seal against leakage.
Relief Valve RV3	Fails to relieve.	0.00005	Relieves supply tank overpressure through C3 in case of an extended hold prior to launch and heat leak into tank more than VCS coolant can handle.	Overpressure of supply tank. See Remarks.	Electrical failure. SOV3 would be closed and VCS coolant flow shutdown.	SOV3/PT10.		Ground use only. This failure is beyond the Single Point Failure Concept.
	Fails open.			Unable to fill and pressurize supply tank.				Change relief valve.
Solenoid Operated Valve SOV6	Fails to open.	0.00081	GH_2 vent valve for filling supply tank.	Unable to completely fill and pressurize supply tank.	Electrical failure.			Change valve.
	Fails to close (includes leaks).			Same as above.				Change valve.

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Solenoid Operated Valve SOV17	Fails to open.	0.00081	Normally closed. Opens to fill PV1-4 with gaseous He at 28.9 MPa (4200 psia).	Unable to fill PV1-4.	Electrical failure.			Filled prior to pallet insertion in Shuttle. Replace valve.
	Fails to close after opened (includes leaks).		Closes to lock off PV1-4 when filled and pressurized.	Loss of pressurization.				Filled prior to pallet insertion in Shuttle. Replace valve.
Solenoid Operated Valve SOV19	Fails to open.	0.00081	Normally closed. Opens to fill PV5-9 with gaseous He at 20.7 MPa (3000 psia).	Unable to fill.	Electrical failure.			Filled prior to pallet insertion in Shuttle. Replace valve.
	Fails to close after opened (includes leaks).		Closes to lock off PV5-9 when filled and pressurized.	Loss of pressurization.				Filled prior to pallet insertion in Shuttle. Replace valve.
Solenoid Operated Valve SOV20	Fails to open.	0.00081	Normally closed. Opens to allow PV1-4 to vent. Closes to prevent H_2 contamination after PV1-4 has been vented.	Unable to vent. If PV1-4 not depleted through normal use, Shuttle will land with PVs partially pressurized.	Electrical failure.	PT8		
	Fails to close after opened (includes leaks).			Possible H_2 contamination of He PVs.				
Solenoid Operated Valve SOV18	Fails to open.	0.00081	Normally closed. Opens to allow PV 5-9 to vent. Closes to prevent H_2 contamination after PV5-9 has been vented.	Unable to vent PVs 5-9. If PV5-9 not depleted through normal use, Shuttle will land with PVs partially pressurized.	Electrical failure.	PT9		

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE II (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Solenoid Operated Valve SOV18	Fails to close after opened (includes leaks).			Possible H_2 contamination of He PVs.				
Temperature Sensors TS8 and TS9	Fails to send signal to DACS. Sends false signal to DACS.	0.00005	Senses temperature of pressurized He gas and sends signal to DACS.	DACS will utilize signal from temperture sensors and pressure transducer to determine He quantity remaining. If DACS senses quantity of remaining He is just sufficient to dump remaining LH_2 and inert supply tank, the experiment will be aborted and the tank dumped and inerted.	Electrical failure.	PT8/PT9.		Experiment terminated.
Pressure Transducers PT8 and PT9	Fails to send signal to DACS. Sends false low signal.	0.00045	Senses pressure of FVs 1-4/PVs 5-9 as applicable and sends signal to DACS. DACS will open SOV19/20 if pressure in He line is over pressure.	DACS will utilize signal from temperture sensors and pressure transducer to determine He quantity remaining. If DACS senses quantity of remaining He is just sufficient to dump remaining LH_2 and inert supply tank, the experiment will be aborted and the tank dumped and inerted.	Electrical failure.	SOV19/SOV20 as applicable. TS8/TS9.		Experiment terminated.

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE II (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Pressure Transducers PT8 and PT9	Sends false high signal.			DACS will send signal to sequentially open SOV1 and then SOV19/SOV20 (as applicable). Could deplete entire contents of applicable hign pressure He system.				Could terminate experiment. Unable to dump or inert supply tank.
Solenoid Operated Valves SOV10/SOV9	Fails to open (SOV10 or SOV9).	0.00081	Receives signal from PT1 (supply tank pressure) through DACS. If PT10 senses low pressure, SOV10 will open and then close. SOV9 will then open and close to allow He pressurant in the supply tank.	None. DACS will sense sequence failure and shift operation to SOV 12 and 13.	Electrical failure.	False high signal from PT10.		
	Fails to close after open (including leaks).			None. DACS will sense sequence failure and shift operation to SOV 12 and 13.		False low signal from PT10.		
Solenoid Operated Valves SOV12/SOV11	Fails to open (SOV12 or SOV11).	0.00081	Normally closed. Redundant system for SOV10/SOV9. If SOV10/SOV9 fails to operate in proper sequence, DACS will automatically shift operation to SOV 12/SOV11.	See Remarks.	Electrical failure. See Remarks.	False high signal from PT10.		This failure is beyond the Single Point Failure Concept. For SOV 12 or SOV11 to fail, SOV10 or SOV9 would have failed first.

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE II (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Upstream Remarks
Flow Control Valve FCV1	Fails to open.	0.00056	Receives signal from DACS using supply tank pressure and flow rate to maintain scheduled flow.	Flow to receiver tank reduced.	Electrical failure.	PT10, QM2.		May be sufficient to terminate experiment.
				Flow stopped to receiver tank.	Electrical failure.			Experiment terminated.
	Fails to close (including leaks).			Unable to maintain scheduled flow.	Electrical failure.			Flow terminated by SOV7 and SOV8.
Check Valve CV1	Fails open.	0.00005	Prevents pressure surges upstream of CV1 from returning to supply tank.	Reversed flow could force liquid in supply tank away from screen device and allow gaseous pressurant to penetrate screen.				When pressure surges in CV1 line terminated, cycle could continue and fluid in receiver tank would be degraded.
	Fails closed.			Flow stopped to receiver tank.	Contaminants in LH_2 or supply tank.			Experiment terminated.
Quality Meter QM2	Sends false high signal to DACS.	0.0015	Measures volumetric flow rate (q) and density (ρ) of supply tank fluid. Sends signal to DACS to determine mass flow rate of liquid from supply tank. In conjunction with QM1 and QM3, will determine accuracy of mass gauging system.	Reduced flow from supply tank to receiver tank. Unable to calibrate mass gauging system.				Primarily used in conjunction with QM1 and QM3 to determine accuracy of mass gauging system.
	Sends false low signal to DACS.			Increased flow from supply tank to receiver tank. Unable to calibrate mass gauging system.				
	Fails to send signal.			Could shut down FCV1.	Electrical failure.			Experiment terminated.

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE II (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Temperature Sensor TS4	Sends false low/high signal to DACS.	0.00005	Senses temperature of liquid downstream of QM2. Sends signal to DACS for information only.	None. Temperature is for information only.				None.
	Fails to send signal.			Same as above.	Electrical failure.			
Pressure Transducer PT4	Sends false low/high signal to DACS.	0.00045	Senses pressure of liquid downstream of QM2. Sends signal to DACS for information only.	None. Signal is for information only.				None.
	Fails to send signal.			Same as above.	Electrical failure.			
Solenoid Operated Valve SOV7	Fails to open.	0.00081	Normally closed. Opens to allow liquid from supply tank to receiver tank.	No flow from supply tank to receiver tank.	Electrical failure.			Supply tank liquid could be vented through SOV8 and SOV1.
	Fails to close (including leaks).			Could overpressure receiver tank.				RV2 will relieve pressure over 276 KPa (40 psia).
Relief Valve RV4	Fails to relieve.	0.00005	Relieves trapped pressure in line between FCV1 and SOV7.	Overpressure of line between FCV1 and SOV7.		Electrical failure. FCV1 and SOV7.		PT4 can sense overpressure in line. SOV8 could be opened to relieve overpressure. Line can withstand 6.895 MPa (1000 psi).
	Fails open.			The line between RV4 and SOV1/BD1 would be pressurized from 276 to 414 KPa (40 to 60 psia). When on orbit and SOV1 is opened, supply tank pressure will be vented.				Experiment terminated.

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE II (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Temperature Sensor TS7	Sends false low/high signal to DACS.	0.00005	Senses temperature of liquid entering receiver tank. Sends signal to DACS for information only.	None. Temperature is for information only.				
	Fails to send signal.			Same as above.	Electrical failure.			
Pressure Transducer PT7	Sends false low/high signal to DACS.	0.00045	Senses pressure of liquid entering receiver tank. Sends signal to DACS for information only.	None. Signal is for information only.				
	Fails to send signal.			Same as above.	Electrical failure.			
Temperature Sensors TS13-29	Sends false low/high signal to DACS.	0.00005	Senses temperature of liquid within receiver tank. Used to determine average tank temperature during prechill. Sends signal to DACS for information during transfer of fluid in and out of receiver tank.	None. Temperature is for information only.				
	Fails to send signal.			Same as above.	Electrical failure.			
Temperature Sensor TS2	Sends false low/high signal to DACS.	0.00005	Senses temperature of liquid exiting receiver tank. Sends signal to DACS for comparison.	None. Temperature is for information only.				
	Fails to send signal.			Same as above.	Electrical failure.			

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE II (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Pressure Transducer PT2	Sends false low signal to DACS.	0.00045	Senses receiver tank pressure and sends signal to DACS. If pressure is excessive, DACS will open SOV22 to increase VCS flow. If this is insufficient, DACS will open SOV4 to relieve pressure.	Could overpressure receiver tank.				RV2 will relieve overpressure if SOV4 fails to open.
Quality Meter QM3	Sends false high/low signal to DACS.	0.0015	Measures volumetric flow rate ($\dot{q}$) and density (ρ) of fluid. Sends signal to DACS to determine mass flow rate of liquid leaving receiver tank. In conjunction with QM1 and QM2, will determine accuracy of mass gauging system.	Unable to calibrate mass gauging system.				
	Fails to send signal.			Same as above.	Electrical failure.			
Solenoid Operated Valve SOV4	Fails to open.	0.00081	Normally closed. Opens when PT4 senses high pressure in receiver tank and when fluid leaves the receiver tank.	a. If opening was for high receiver tank pressure, no effect. RV2 will relieve excess pressure.	Electrical failure.	False low pressure. Signal from PT2.		a. RV2 will relieve excess pressure.
				b. If opening was to vent receiver tank fluid, no flow will leave tank through SOV4. Experiment terminated.				b. Could blow down receiver tank through SOV7 and SOV8. Close SOV7 and blow down supply tank through FCV1 and SOV8.

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE II (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Solenoid Operated Valve SOV4	Fails to close after opened (including leaks).			a. If fails to close, receiver tank will be blown down down through SOV1. b. If leak is very small, no effect.		False high pressure signal from PT2.		a. Experiment terminated. Could inert receiver by first venting supply tank and closing SOV3. Close SOV1 and inert receiver tank.
Relief Valve RV2	Fails to relieve. See Remarks.	0.00005	Redundant protection from overpressure of receiver tank.	Overpressure of receiver tank. See Remarks.				This failure is beyond the Single Point Failure Concept. Before RV2 could fail to relieve, the tank would have to have excess pressure and SOV4 would have to fail to open.
	Fails open.			Receiver tank will be blown down through SOV1.				Experiment terminated. Could inert receiver by first venting supply tank and closing SOV3. Close SOV1 and inert receiver tank.
Solenoid Operated Valves SOV14/SOV13	Fails to open (SOV14 or SOV 13).	0.00081	Normally closed. Receives signal from PT2 (receiver tank pressure) through DACS. If PT2 senses low pressure, SOV14 will open and then close. SOV13 will then open and close to allow He pressurant from PV5-9 to enter the receiver tank.	None. DACS will sense sequence failure and shift operation to SOV 16 and 15.	Electrical failure.	False high signal from PT2.		

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE II (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Solenoid Operated Valves SOV14/SOV 13	Fails to close after open (including leaks).			Same as above.		False low signal from PT10.		
Solenoid Operated Valves SOV16/SOV 15	Fails to open (SOV16 or SOV 15).	0.00081	Normally closed. Redundant system for SOV14/SOV13. If SOV14/SOV13 fail to operate in proper sequence.	See Remarks.	Electrical failure. See Remarks.			This failure is beyond the Single Point Failure Concept. For SOV 16 or SOV15 to fail, SOV14 or SOV13 would have failed first.
	Fails to close after open (including leaks).			See Remarks.				
Filter F2	Filter clogs.	0.00001	Filters high pressure GHe flow to FO3.	Reduced/shutoff of flow through filter and orifice, and reduced pressurant to receiver tank.	Contaminated filter at GHe interface.			He should be filtered prior to ground fill interface.
Flow Orifice FO3	Clogged orifice.	0.00001	Reduces high pressure GHe to pressure of 276 KPa (40 psi) by choking flow.	Shutoff of He pressurant to receiver tank.	Filter clogging or disintegration. See Remarks.	Filter F2.		This is beyond Single Point Failure Concept.
Temperature Sensor TS6	Sends false signal (high or low). Fails to send signal.	0.00005	Senses temperature of GHe after passing through FO3. Signal received by DACS.	None. DACS uses signal for expulsion pressurant information only.	Flow reduction from clogged filter or orifice. Electrical failure.	F2/FO3.		
Pressure Transducer PT6	Sends false signal (high or low). Fails to send signal.	0.00045	Senses pressure of GHe after passing through FO3. Signal received by DACS.	None. DACS uses signal for expulsion pressurant information only.	Flow reduction from clogged filter or orifice. Electrical failure.	F2/FO3.		

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE II (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Solenoid Operated Valve SOV8	Fails to open.	0.00081	Normally closed. Vent valve for supply tank (blowdown). When open, allows fluid from supply tank to be vented. Also used as vent for He purge, mass gauging system calibration, and QM2 calibration.	a. During blowdown: Unable to blow down tank and purge in normal manner. See Remarks.	Electrical failure.			a. Could blow down through receiver tank if sufficient He pressurant is available.
				b. During He purge: Unable to purge in normal manner. Unable to calibrate QM2.				b. Purge could be vented through receiver tank after fluid in receiver tank vented.
	Fails to close (including leaks).			a. Unable to transfer liquid to receiver tank.				a. Experiment terminated.
				b. If leak is small, no effect.				b. If leak is large, see a.
Heat Exchanger HX1	Fails to operate.	0.00081	Electrical heat exchange. Will heat liquid to vapor stage. Receives signal from TS5/PT5 through DACS.	Inaccurate measurement from VM1. Will be unable to calibrate quality meter.	Electrical failure.	Inaccurate signal from TS5/PT5.		
	Fails to turn off.			Possibility of overheating line.				Thermostatically protected.
Pressure Transducer PT5	Sends false high signal.	0.00045	Senses pressure of vapor upstream of HX1. Sends signal to DACS. If pressure is below saturation pressure, DACS will turn on HX1.	HX1 would operate longer than required resulting in warming fluid above saturation pressure. Would tend to invalidate quality meter calibration.				If PT5 malfunctions, only the mass gauging system calibration would be jeopardized.

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE II (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Pressure Transducer PT5	Sends false low signal.			HX1 would turn off prior to fluid reaching saturation pressure resulting in invalid quality meter calibration.				
	Fails to send signal.			HX1 may not operate resulting in cold fluid reaching VM1. Invalid quality meter calibration.	Electrical failure.			
Temperature Sensor TS5	Sends false high signal.	0.00005	Senses temperature of vapor upstream of HX1. Sends signal to DACS. If temperature below saturation temperature, DACS will turn on HX1.	HX1 would turn off prior to reaching saturation temperature resulting in invalid quality meter calibration.				If TS5 malfunctions, only the mass gauging system calibration would be jeopardized.
	Sends false low signal.			HX1 would operate longer than required resulting in warmer fluid above saturation temperature. Would tend to invalidate quality meter calibration.				
	Fails to send signal.			HX1 may not operate resulting in cold fluid reaching VM1. Invalid quality meter calibration.	Electrical failure.			

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE II (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Heat Exchanger HX2	Fails to operate (if electrical).	0.00081	Warms fluid from HX1 prior to VM1 to insure an accurate reading from VM1.	Inaccurate measurement from VM1. Will be unable to calibrate mass gauging system.	Electrical failure.			
	Fails to turn off (if electrical).			None. Unit will be on during flow through SOV8.				Thermostatically protected (if electrical).
Volumetric Meter VM1	Sends false low/high signal to DACS.	0.00015	Measures volumetric flow rate (q) of flow through vent line. Signal sent to DACS and used for calibration of QM2 and mass gauging system.	Inaccurate calibration of QM2.				
	Fails to send signal.			Same as above.	Electrical failure.			
Temperature Sensor TS10	Sends false low/high signal to DACS.	0.00005	Senses temperature of vapor from VM1. Sends signal to DACS for information only.	None. Used for information only.				May be used to control HX2 if HX2 is electrical.
	Fails to send signal.			Same as above.	Electrical failure.			
Quality Meter QM1	Sends false signal to DACS (high/low).	0.0015	Measure volumetric flow rate (q) and density (ρ) of VCS coolant fluid. Sends signal to DACS to determine flow rate of fluid through VCS. In conjunction with QM2 and QM3, will determine accuracy of mass gauging system. Determines effectiveness of VCS.	Inaccurate mass gauging system calibration.				
	Fails to send signal.			Same as above.	Electrical failure.			

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE II (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Temperature Sensor TS1	Sends false signal to DACS (high/low).	0.00005	Senses temperature of VCS coolant exiting QM1. Sends signal to DACS.	None. Signal is for information only.				
	Fails to send signal.			Same as above.	Electrical failure.			
Pressure Transducer PT1	Sends false signal to DACS (high/low).	0.00045	Senses pressure of VCS coolant exiting QM1. Sends signal to DACS.	None. Signal is for information only.				
	Fails to send signal.			Same as above.	Electrical failure.			
Solenoid Operated Valve SOV3	Fails to open.	0.00081	Normally closed. Opens to allow flow of VCS fluid to vent. Receives signal from DACS to open when PT 10 senses high pressure in supply tank.	No flow through VCS. Increased heat leak due to less cooling through VCS causing increased pressure in supply tank.	Electrical failure.	False low signal from PT10.		If overpressure of supply tank is imminent, RV1 will relieve pressure.
	Fails to close (includes leaks).			a. Depletion of supply tank fluid.		False high signal from PT10.		a. Experiment terminated.
				b. Leaks: If minor leak, no effect.				b. If leak is large, see a.
Pressure Transducer PT10	Sends false low signal to DACS.	0.00045	Senses supply tank pressure. If pressure is high, will send signal through DACS to open SOV 3 to increase VCS coolant fluid to decrease heat leak.	Will close SOV3 to reduce VCS coolant and increase heat leak to supply tank. Increase of supply tank pressure. See Remarks.				If pressure is excessive, RV1 will relieve pressure.

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE II (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Pressure Transducer PT10	Sends false high signal to DACS.			Will open SOV3 to increase VCS coolant. Partial depletion of supply tank fluid. Decrease of pressure in supply tank.				
	Fails to send signal to DACS.			DACS could interpret signal as low pressure signal and close SOV3. Pressure in tank will increase due to increased heat leak. See Remarks.	Electrical failure.			If pressure is excessive, RV1 will relieve pressure.
Relief Valve RV1	Fails to relieve. See Remarks.	0.00005	Protective valve to prevent overpressure of supply tank in case of FCV1 and SOV3 failure to open or electrical failure.	Overpressure of supply line. See Remarks.	Electrical failure.			This failure is beyond the Single Point Failure Concept. Before RV1 could fail to relieve, FCV1 and SOV 3 would first have to fail closed (for instance, electrical failure).
	Fails open.			Loss of pressure of of supply tank.				Experiment terminated.

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE II (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Solenoid Operated Valve SOV1	Fails to open.	0.00081	Normally closed until "on orbit," then normally open. Vent valve to orbiter interface vent. Opens at other times as follows: a. PT8 senses overpressure of PV1-4 and SOV20 opens. b. PT9 senses overpressure of PV5-9 and SOV18 opens. Closed after experiment completed for He purge and pad.	Experiment terminated. See Remarks.	Electrical failure.	PT8/SOV20, PT9/SOV18.		System protected against overpressure by BD1.
	Fails to close (including leaks).			Unable to have He pad after purge.				
Burst Disc BD1	Fails to burst. See Remarks.		Protective system to prevent overpressure of entire system.	Overpressure of system. See Remarks.				This failure is beyond the Single Point Failure Concept.
Solenoid Operated Valve SOV2	Fails to open.	0.00081	Normally closed. Horizontal drain valve. Open only for ground LH_2 drain to C3 (T-O umbilical). (Used only if system failure results in LH_2 in supply tank upon landing.)	Unable to drain LH_2 through SOV 2. See Remarks.	Electrical failure.			Ground use only. Could partially empty supply tank through SOV5 and then hook up GHe supply to C6 to vaporize remaining LH_2. Change valve after inert.
	Fails to close (includes leaks).			None. At T-O C3 umbilical disconnected and sealed. See Remarks.				When C3 umbilical disconnected, provides seal against leakage.

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE II (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Solenoid Operated Valve SOV5	Fails to open.	0.00081	Normally closed. Vertical drain valve. Open only for ground LH_2 drain on launch pad to C3 (T-O umbilical).	Unable to drain LH_2 through SOV 5. See Remarks.	Electrical failure.			Ground use only. Could partially empty supply tank through SOV2 and then hook up GHe supply to C6 to vaporize remaining LH_2. Change valve after inert.
	Fails to close (includes leaks).			None. At T-O C3 umbilical disconnected and sealed. See Remarks.				When C3 umbilical disconnected, provides seal against leakage.
Relief Valve RV3	Fails to relieve.	0.00005	Relieves supply tank overpressure through C3 in case of an extended hold prior to launch and heat leak into tank more than VCS coolant can handle.	Overpressure of supply tank. See Remarks.	Electrical failure. SOV3 would be closed and VCS coolant flow shutdown.	SOV3/PT10.		Ground use only. This failure is beyond the Single Point Failure Concept.
	Fails open.			Unable to fill and pressurize supply tank.				Change relief valve.
Solenoid Operated Valve SOV6	Fails to open.	0.00081	GH_2 vent valve for filling supply tank.	Unable to completely fill and pressurize supply tank.	Electrical failure.			Change valve.
	Fails to close (includes leaks).			Same as above.				Change valve.
Mass Quantity Gauge 2	Fails to measure.	Unknown	Supply tank quantity measurement.	Unable to determine amount of liquid in tank.	Electrical failure.			

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE II (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Mass Quantity Gauge 2	Radiation source tube rupture.			Releases radioactive Krypton 85 gas.	Mechanical failure.			Less than 600 millicuries of Krypton 85 will be released. Tube is aluminum alloy (0.250 OD with 0.045 wall thickness) and hard anodized. Tube ends cold welded and then epoxyed.
Flow Orifice FO4	Orifice clogs.	0.00001	Reduces pressure and controls flow of LH_2 from receiver tank to VCS.	Loss of thermal control of receiver tank. Could overpressure receiver tank.	Contaminants in LH_2 or receiver tank.	Filters F1 and F2.		Can vent VCS through SOV22 if identifiable from temperature sensors within receiver tank and/or TS11 and PT11. RV2 will relieve overpressure of receiver tank.
Quality Meter QM5	Sends false signal to DACS (high/low).	0.00015	Measures volumetric flow rate (q) and density ( ) of VCS coolant fluid. Sends signal to DACS to determine flow rate of fluid through VCS. In conjunction with QM1, QM2, QM3 and QM4, will determine accuracy of mass gauging system. Determines effectiveness of VCS.	Inaccurate mass gauging system calibration.				
	Fails to send signal.			Same as above.	Electrical failure.			

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE II (Continued)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Temperature Sensor TS11	Sends false signal to DACS (high/low).	0.00005	Senses temperature of VCS coolant exiting QM5. Sends signal to DACS.	None. Signal is for information only.				
	Fails to send signal.			Same as above.	Electrical failure.			
Pressure Transducer PT11	Sends false signal to DACS (high/low).	0.00045	Senses pressure of VCS coolant exiting QM5. Sends signal to DACS.	None. Signal is for information only.				
	Fails to send signal.			Same as above.	Electrical failure.			
Solenoid Operated Valve SOV22	Fails to open.	0.00081	Normally closed. Opens to allow flow of VCS fluid to vent. Receives signal from DACS to open when PT2 senses high pressure in receiver tank.	No flow through VCS. Increased heat leak due to less cooling through VCS causing increased pressure in receiver tank.	Electrical failure.	False low signal from PT2.		If overpressure of receiver tank is imminent, RV2 will relieve pressure.
	Fails to close (includes leaks).			a. Depletion of receiver tank fluid. b. Leaks - if minor.		False high signal from PT2.		a. Experiment terminated. b. If leak is large, see a.
Flow Control Valve FCV2	Fails to open.	0.00056	Receives signal from DACS using receiver tank pressure and flow rate to maintain scheduled flow.	Flow to QM4 terminated.	Electrical failure.	PT2, QM4.		May vent fluid in receiver tank through SOV4.
	Fails to close (includes leaks).		Unable to maintain scheduled flow.	Unable to meter flow of fluid to QM5.	Electrical failure.	PT2, QM4.		May be sufficient to terminate experiment. Flow can be terminated by SOV21.

APPENDIX I CFMF FAULT HAZARD ANALYSIS, PHASE II (Concluded)

Component	Component Failure Mode	Component Failure Rate (Primary)	System Operational Mode	Effect of Primary Component Failure on Subsystem	Factors That May Cause Secondary Component Failure	Upstream Components or Inputs That May Cause Sequential Failures	Further Analysis Required	Remarks
Solenoid Operated Valve SOV21	Fails to open.	0.00081	Normally closed. Opens to allow receiver tank fluid to SOV8 or FCV2 and supply tank fluid into start basket.	Will not allow fluid from receiver tank to SOV8 or FCV2 and prevents filling of start basket.	Electrical failure.			Experiment terminated. May vent fluid in receiver tank through SOV4.
	Fails to close (includes leaks).			None. FCV2 and SOV8 can terminate flow as required.				
Quality Meter QM4	Sends false high signal to DACS.	0.00015	Measures volumetric flow rate (q) and density ( ) of receiver tank fluid. Sends signal to DACS to determine mass flow rate of liquid from receiver tank. In conjunction with QM1, QM2, QM3, QM5 and VM1 will determine accuracy of mass gauging system.	Reduced flow from receiver tank to vent. Unable to calibrate mass gauging system.				Primarily used in conjunction with QM1, QM2, QM3, QM5 and VM1 to determine accuracy of mass gauging system.
	Sends false low signal to DACS.			Increased flow from receiver tank. Unable to calibrate mass gauging system.				
	Fails to send signal.			Could shut down FCV2.	Electrical failure.			Experiment terminated.

APPENDIX II

BILL OF MATERIAL

APPENDIX II CFMF BILL OF MATERIAL

Part Identification	Component	Specification	Quantity	Lead Time
	PHASE I AND PHASE II			
SOV1 SOV3 SOV4 SOV6	Solenoid Operated Valve	12.7 mm (1/2"), 28 vdc, Shuttle payload rated, normally closed, maximum pressure 689.5 KPa (100 psia), cryo rated 20°K (36°R), LH_2	4 req	18 wks
SOV2 SOV7 SOV8	Solenoid Operated Valve	9.5 mm (3/8"), 28 vdc, Shuttle payload rated, normally closed, maximum pressure 689.5 KPa (100 psia), cryo rated 20°K (36°R), LH_2	3 req	18 wks
SOV10 SOV12 SOV13 SOV15	Solenoid Operated Valve	6.35 mm (1/4"), 28 vdc, Shuttle payload rated, normally closed, maximum pressure 689.5 KPa (100 psia), cryo rated 20°K (36°R), LH_2	4 req	18 wks
SOV9 SOV11 SOV14 SOV16 SOV17 SOV18 SOV19 SOV20	Solenoid Operated Valve	6.35 mm (1/4"), 28 vdc, maximum temperature 60°C (140°F), Shuttle rated, normally closed, GHe, maximum pressure 31 MPa (4500 psia)	8 req	18 wks
TS1 TS2 TS4 TS5 TS7 TS10	Temperature Sensor	Immersion type, cryo rated 20°K (36°R), platinum Resistive Thermal Device, external connector, maximum pressure 689.5 KPa (100 psia)	6 req	26 wks

APPENDIX II CFMF BILL OF MATERIAL (Continued)

Part Identification	Component	Specification	Quantity	Lead Time
TS3 TS6	Temperature Sensor	Immersion type, maximum temperature 60°C (140°F), external connector, maximum pressure 689.5 KPa (100 psia), Shuttle rated, platinum RTD	2 req	26 wks
TS8 TS9	Temperature Sensor	Immersion type, maximum temperature 60°C (140°F), external connector, maximum pressure 31 MPa (4500 psia), Shuttle payload rated, platinum RTD	2 req	26 wks
TS13 to TS62	Temperature Sensor	Surface contact type, cryo rated 13 to 400 $^{\circ}$K (23 to 720°R), platinum RTD, maximum pressure 689.5 KPa (100 psia), Shuttle payload rated	49 req	26 wks
PT1 PT2 PT4 PT5 PT7 PT10	Pressure Transducer	Cryo rated 20°K (36 $^{\circ}$R), 10 vdc, pressure rating 0 to 689.5 KPa (0 to 100 psia), Shuttle rated	6 req	12 wks
PT3 PT6	Pressure Transducer	Maximum temperature 60°C (140°F), 10 vdc, pressure rating 0 to 689.5 KPa (0 to 100 psia), Shuttle rated	2 req	12 wks
PT8 PT9	Pressure Transducer	Maximum temperature 60°C (140°F), 10 vdc, pressure rating 0 to 31 MPa (0 to 4500 psia), Shuttle rated	2 req	12 wks

APPENDIX II CFMF BILL OF MATERIAL (Continued)

Part Identification	Component	Specification	Quantity	Lead Time
QM1 QM2 QM3 QM4 QM5	Quality Meter	Cryo rated 20°K (36 °R), 28 vdc, maximum pressure 689.5 KPa (100 psia), Shuttle rated, measures percent vapor and density, flow rated 0 to .55 lb/sec of LH_2	5 req	52 wks
VM1	Volumetric Flow Meter (Turbine Type)	Maximum temperature 60°C (140°F), 28 vdc, must not freeze at cryo temperatures of LH_2, maximum pressure 689.5 KPa (100 psia), Shuttle rated	1 req	52 wks
FCV1	Flow Control Valve	9.5 mm (3/8"), 115 vac, 400 Hz, maximum pressure 689.5 KPa (100 psia), cryo rated 20°R (36°K), normally closed, step motor operated, Shuttle rated, LH_2	1 req	17 wks
RV1	Relief Valve	12.7 mm (1/2"), cryo rated 20°K (36°R), relief pressure 689.5 KPa (100 psia), Shuttle rated	1 req	18 wks
RV2	Relief Valve	12.7 mm (1/2"), cryo rated 20°K (36°R), relief pressure 344.7 KPa (50 psia), Shuttle rated	1 req	18 wks
RV3 RV4	Relief Valve	9.5 mm (3/8"), cryo rated 20°K (36°R), relief pressure 689.5 KPa (100 psia), Shuttle rated	2 req	18 wks

APPENDIX II CFMF BILL OF MATERIAL (Continued)

Part Identification	Component	Specification	Quantity	Lead Time
CV1	Check Valve	9.5 mm (3/8"), maximum pressure 689.5 KPa (100 psia), cryo rated 20°K (36°R), LH_2, Shuttle rated	1 req	18 wks
HX1 HX2	Heat Exchanger	9.5 mm (3/8"), cryo rated 20°K (36°R), maximum pressure 689.5 KPa (100 psia), wattage 2080 watts/hour	2 req	20 wks
F1 F2	Filter	6.35 mm (1/4"), maximum temperature 60°C (140°F), He, maximum particle passage 125 microns	2 req	12 wks
FO2 FO3	Flow Orifice	6.35 mm (1/4"), inlet, maximum temperature 60°C (140 °R), maximum pressure 689.5 KPa (100 psia)	2 req	10 wks
BD1	Burst Disc	12.7 mm (1/2"), maximum temperature 60°C (140°R), relief pressure 137.9 KPa (20 psia)	1 req	12 wks
Pressurization Bottles	256.5 dia x 795 lg (10.0 dia x 31.3 lg) 26.7 liters (1631 cu in) at 95.1 KPa (3000 psig)	Kevlar wound over 6061 aluminum bottle	5 req	6 wks
Subpallet	76.2 x 36.8 x 6261.1 (3 x 1.5 x 246.5) channel	6061-T6 aluminum channel	6261.1 (246.5)	2 wks
Straps	76.2 x 1.59 x 14,986 lg (3 x 1/16 x 590 lg)	Aluminum sheet	14,986 (590)	2 wks

APPENDIX II CFMF BILL OF MATERIAL (Continued)

Part Identification	Component	Specification	Quantity	Lead Time
Cable	3.2 dia x 2235.2 (1/8 x 88)	Steel cable	2235.2 (88)	2 wks
Fill Tube (Vacuum Jacketed) (CFME)	12.7 x 960.12 x .7 (1/2 x 37.8 x .028), 1" Sch 40 pipe outer shell	304L CRES	960.12 (37.8)	10 wks
Pressurization Tube (CFME)	6.4 x 1280.2 x .5 (1/4 x 50.4 x .020)	304L CRES	1280.2 (50.4)	4 wks
Horizontal Drain Tube (CFME)	9.5 x 960.12 x .5 (3/8 x 37.8 x .020)	304L CRES	960.12 (37.8)	4 wks
Drain (CFME)	12.7 x 960.12 x .7 (1/2 x 37.8 x .028)	304L CRES	960.12 (37.8)	4 wks
Vent Tube (CFME)	12.7 x 1280.2 x .7 (1/2 x 50.4 x .028)	304L CRES	1280.2 (50.4)	4 wks
Bayonet	Male Bayonet	304L CRES, 12.7 x .7 wall of inner tube (1/2 x .028)	1 req	16 wks
	PHASE I			
Channel (Receiver Support)	76.2 x 38.1 x 8991.6 (3 x 1.5 x 354)	6061 aluminum	8991.6 (354)	2 wks
Insulation	335 m^2 (3606 ft^2)	Double Kapton MLI, superfloc	3606 ft^2	32 wks
Instrumentation Tree	S-glass Epoxy Tube	50.8 dia x 5994.4 (2 x 236") S-glass epoxy tube	1 req	8 wks
Insulation Fasteners	50.8 x 101.6 (2 x 4) velcro patches	60 patches, 50.8 x 101.6 (2" x 4" sq)	1/2 lot	2 wks
Struts	Support Struts	S-glass epoxy tubes, see drawing, sheet 15, for sizes	8 req	16 wks

APPENDIX II CFMF BILL OF MATERIAL (Continued)

Part Identification	Component	Specification	Quantity	Lead Time
PV Head	Elliptical Head, A/B ratio = 1.38 556.25 (21.9) deep x .66 (.026) thick x 1536.7 (60.5)	6061-T6 aluminum	2 req	8 wks
PV Cylinder	Cylinder, 1536.7 (60.5) dia x 1960.9 (77.2) lg x .96 (.038) thick	6061-T6 aluminum	1 req	10 wks
Cirth Ring	152.4 (6.0) wide x 25.4 (1.0) flange x 3.17 (.125) thick 1536.7 (60.5) diameter	6061-T6 aluminum	2 req	26 wks
Fill Tube (Receiver Tank)	9.5 x 3680.5 x .5 (3/8 x 144.9 x .020)	304L CRES	3680.5 (144.9)	4 wks
Bi-Metal Joint	9.5 x .5 (3/8 x .020)	304L CRES/6061 aluminum	1 req	16 wks
Pressurization Tube (Receiver Tank)	6.4 x 7808.9 x .5 (1/4 x 307.4 x .020)	304L CRES	7808.9 (307.4)	4 wks
Bi-Metal Joint	6.4 x .5 (1/4 x .020)	304L CRES, 6061 aluminum	1 req	16 wks
Vent Tube (Receiver)	25.4 x 101.6 x .9 (1 x 4 x .036)	304L CRES	101.6 (4.0)	4 wks
	12.7 x 8747.8 x .7 (1/2 x 344.4 x .028)	304L CRES	8747.8 (344.4)	4 wks
Reducer	25.4 x 12.7 x .9 (1 x 1/2 x .036)	304L CRES	1 req	2 wks
Bi-Metal Joint	25.4 x .9 (1 x .036)	304L CRES, 6061 aluminum	1 req	16 wks
Tee	25.4 x .036 wall (1 x .036 wall)	304L CRES	1 req	2 wks

APPENDIX II CFMF BILL OF MATERIAL (Continued)

Part Identification	Component	Specification	Quantity	Lead Time
Bellows	9.5 x .5 wall (3/8 x .020)	304L CRES	1 req	3 wks
	6.35 x .5 wall (1/4 x .020)	304L CRES	1 req	3 wks
	12.7 x .7 wall (1/2 x .028)	304L CRES	3 req	3 wks
Diffuser (Receiver)			1 req	-
	PHASE II			
SOV21 SOV22	Solenoid Operated rols Valve	9.5 mm (3/8"), 28 vdc, Shuttle payload rated, normally closed, maximum pressure 689.5 KPa (100 psia), cryo rated 20°K (36°R), LH_2	2 req	18 wks
TS13 to TS29	Temperature Sensor	Surface contact type, cryo rated 13 to 400 °K (23 to 720°R), platinum RTD, maximum pressure 689.5 KPa (100 psia), Shuttle payload rated	17 req	26 wks
PT11	Pressure Transducer	Cryo rated 20°K (36°R), 10 vdc, pressure rating 0 to 689.5 KPa (0 to 100 psia), Shuttle rated	1 req	12 wks
FCV2	Flow Control Valve	9.5 mm (3/8"), 115 vac, 400 Hz, maximum pressure 689.5 KPa (100 psia), cryo rated 20°R (36°K), normally closed, step motor operated, Shuttle rated, LH_2	1 req	18 wks

APPENDIX II CFMF BILL OF MATERIAL (Continued)

Part Identification	Component	Specification	Quantity	Lead Time
PV Head (Receiver)	Elliptical Head, A/B ratio = 1.38, 254 (10) deep x 685.8 (27) dia x .64 (.025) thick	6061-T6 aluminum	2 req	8 wks
Girth Ring	101.6 (4) wide x 25.4 (1) flange with 76.2 (3) burndown edge .89 (.035) thick - diameter is 685.8 (27.0)	6061-T6 aluminum	2 req	26 wks
PV Cylinder	685 (27) x 685.8 (27) dia x .64 (.025) thick	6061-T6 aluminum	1 req	10 wks
Fill/Drain Tube	9.5 x .5 x 3096.3 (3/8 x .020 x 121.9)	304L CRES	3096.3 (121.9)	4 wks
Diffuser (Receiver)			1 req	-
Bi-Metal Joint	9.5 x .5 (3/8 x .020)	304L CRES/6061 aluminum	2 req	16 wks
He Inlet Tube	6.35 x 4235.2 x .5 (1/4 x 166.7 x .020)	304L CRES	4235.2 (166.7)	4 wks
Channel	76.2 x 38.1 x 11356.9 (3 x 1.5 x 447.1)	6061-T6 aluminum channel 6.35 (1/4) thick	11356.9 (447.1)	2 wks
Bi-Metal Joint	6.3 x .5 (1/4 x .020)	304L CRES	1 req	16 wks
Fill Tube	9.5 x 4581.9 x .5 (3/8 x 180.4 x .020)	304L CRES	4581.9 (180.4)	4 wks
Vent Tube	12.7 x 10012.7 x .7 (1/2 x 394.2 x .028)	304L CRES	10012.7 (394.2)	4 wks
Bi-Metal Joint	25.4 x .9 wall (1 x .036)	304L CRES/6061 aluminum	1 req	16 wks
Thermo Vent	9.5 x 13479.8 x .5 (3/8 x 530.7 x .020)	Aluminum	13479.8 (530.7)	4 wks

APPENDIX II CFMF BILL OF MATERIAL (Concluded)

Part Identification	Component	Specification	Quantity	Lead Time
Bi-Metal Joint	9.5 x .5 wall (3/8 x .020 w)	6061 to 304L transition	1 req	16 wks
Start Basket			1 req	-
Instrumentation Tree	S-glass/Epoxy Tube	50.8 dia x 3787.1 (2.0" dia x 149.1")	3787.1 (149.1)	8 wks
Insulator Fasteners	50.8 x 101.6 (2 x 4)	40 velcro patches 50.8 x 101.6 (2 x 4 sq)	40 (1/2 lot)	2 wks
Insulation	69.31 m^2 (746 ft^2)	Double kapton MLI, Superfloc	69.31 (746)	32 wks
Struts	S-glass/Epoxy	See drawing, sheet 15, for sizes	8 req	16 wks
Vent Tube	25.4 x 101.6 x .9 (1 x 4 x .036)	304L CRES	101.6 (4.0)	4 wks
Reducer	25.4 x 12.7 x .9 (1 x 1/2 x .036)	304L CRES	1 req	2 wks
Tee	25.4 x .036 (1 x .036 wall)	304L CRES	1 req	2 wks

APPENDIX III

CFMF START BASKET REFILL ANALYSIS

Refilling of the CFMF start basket was evaluated by means of a Beech-developed computer program, REFILL. The program implements a simple Kinematic model of a start basket, shown schematically in Figure III-1. The basket is assumed to be completely submerged in liquid. The liquid level inside the basket is h. Liquid is assumed to flow into the basket through the portion of the mainscreen contacting liquid inside the basket. In Figure III-1, the liquid inflow region is the surface area between $0 \leq x \leq h$. Vapor is assumed to flow out of the basket only through the end of the standpipe. Thermodynamic effects are neglected.

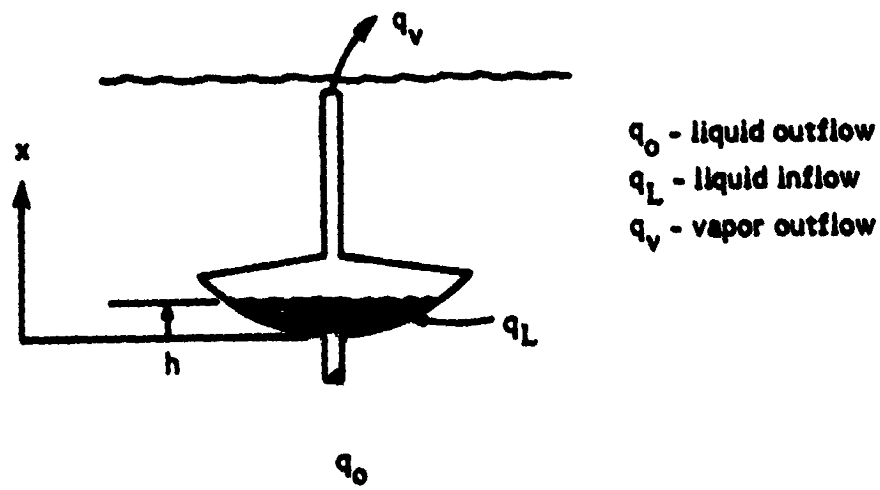

Figure III-1 REFILL MODEL

For a given liquid level inside the basket, a pressure drop equation relating vapor outflow, liquid outflow through the outlet pipe and liquid inflow through the mainscreens can be solved for the net liquid flow into the basket. The time history of the liquid level inside the basket is calculated by the following procedure:

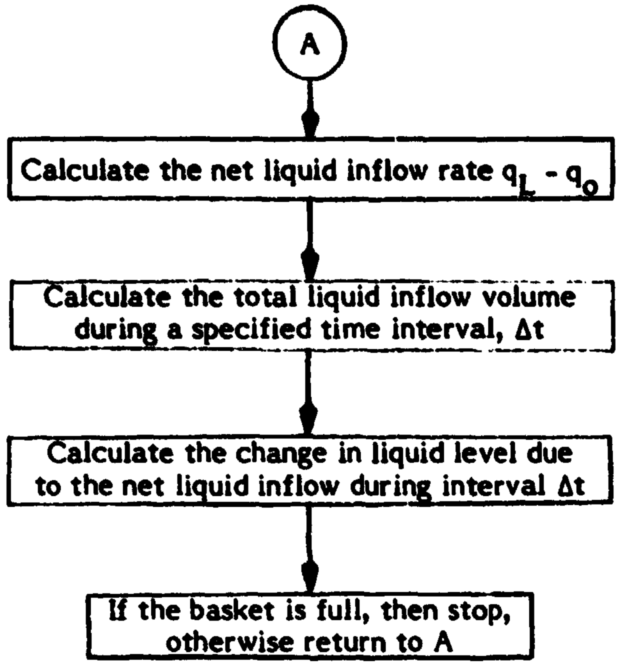

Figure III-2 shows the results of a REFILL calculation for the CFMF start basket with LH_2 and and RCS acceleration of 0.22 m/sec^2 (0.72 ft/sec^2). The initial liquid level in the basket is 11.4 mm (0.445 in). This is based on the assumption that the liquid volume in the basket at the start of refill is essentially the residual volume of 1.76 x 10^{-3} m^3 (0.062 ft^3).

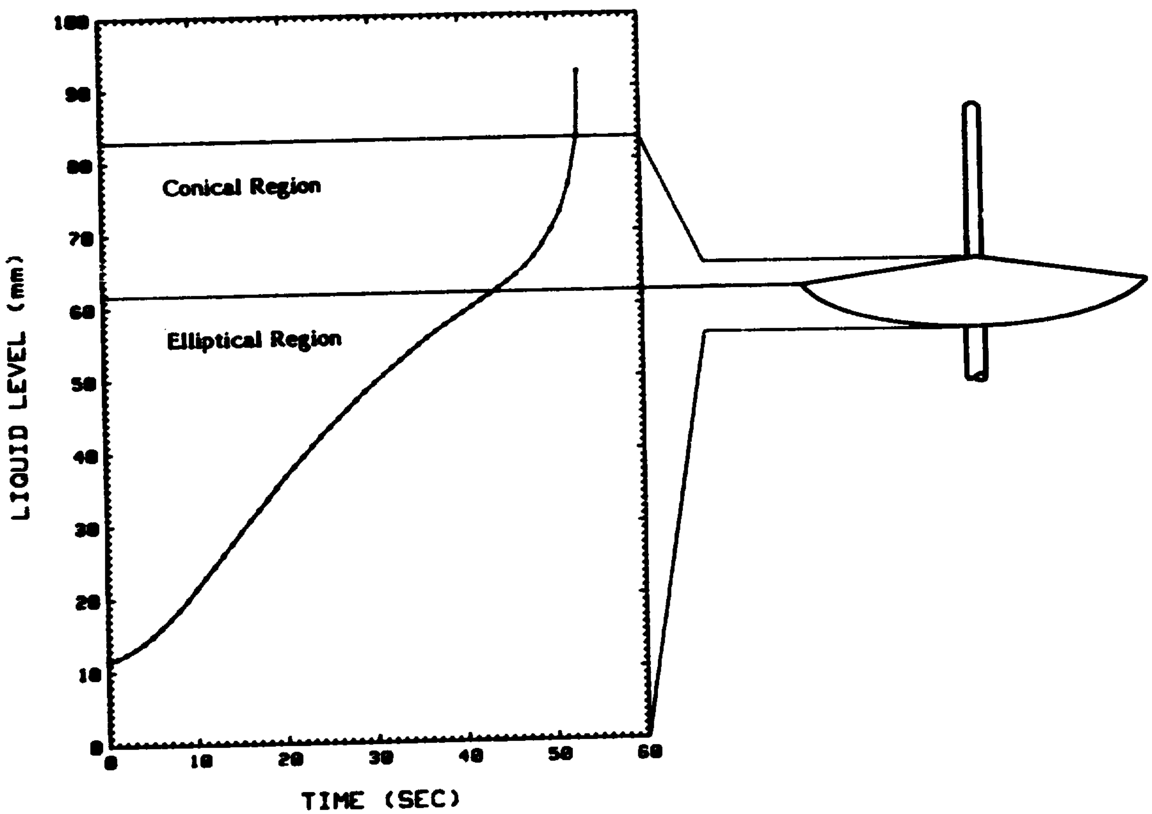

Figure III-2 CFMF START BASKET REFILLING